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An Alternative to EPA Method 9—Field Validation of the Digital Opacity Compliance System (DOCS)

Final Report for ESTCP Project No. CP-200119

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14. ABSTRACT
The Digital Opacity Compliance System (DOCS) software translates images from a commercial digital camera into visual plume opacity measurements, and is proposed as an alternate reporting method to EPA Method 9. Field tests confirmed that, under fair weather conditions, DOCS consistently met prescribed standards for quantitative accuracy and reliability. At real-world industrial operations, accuracy of DOCS's opacity measurements was comparable to Method-9-certified human observers'. Under dark, overcast skies, both DOCS and human readers were less accurate, but DOCS opacity measurements were less compromised, supporting a claim that DOCS is more reliable than Method 9 for all types of stationary sources and under all weather conditions. DOCS will 1) improve measurement objectivity and reliability, 2) lower deployment and maintenance costs and 3) provide permanent digital images of visible opacity--evidence in regulatory enforcement actions. Economic analysis projects $9,011.82 (stateside) and $15,650.10 (remote facilities) annual savings per pair of trained users. DoD certifies 3,400+ Method 9 readers, so DoD-wide adoption of DOCS could decrease compliance costs $15.3M annually, payback occurring in months. Life-cycle cost analysis projects savings of $40,118.82 (stateside) and $69,671.12 (remote) per pair of users, and aggregate DoD financial benefit of $68.2M (assuming five years useful life). Necessary for implementation is concurrence by regulators, which process is underway.

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List of Acronyms

ABW	Airbase wing
AFB	Air Force Base
AFRL	Air Force Research Laboratory
Btu	British thermal unit
CAA	Clean Air Act
CE	Civil engineer
CEM	Continuous emissions monitor
CHP	Chemical hygiene plan
COTS	Commercial off-the-shelf
COM	Continuous opacity monitor
DOCS	Digital Optical Compliance System
DoD	Department of Defense
DQA	Data Quality Assessment
DQO	Data Quality Objective
EMC	EPA Emissions Measurement Center
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ETA	Eastern Technical Associates
IAW	In accordance with
Method 9	40 CFR 60, Appendix C, Method 9, *Visual Determination of Opacity from Stationary Sources*
MLQL	Materials Directorate, Airbase Technologies Division
MMBtu	Million Pounds Fuel per Million British Thermal Units Heat
NASA	National Aeronautical and Space Administration
OAQPS	Office of Air Quality Performance Standards
OEPA	Ohio EPA
OO-ALC	Ogden Air Logistics Center
SOP	Standard operating procedure
US	United States
WPAFB	Wright Patterson Air Force Base
40 CFR	Section 40 of the Code of Federal Regulations

Preface

The following project final report, which summarizes the Digital Opacity Compliance System (DOCS) field demonstration efforts conducted from January 2001 through December 2003, was supported by the Environmental Security Technology Certification Program (ESTCP) under project CP-200119. The report conforms to recent ESTCP guidance developed for completing compliance demonstration project final reports [1].

The authors of this report wish to acknowledge the considerable efforts of government and private contractor personnel from the Air Force Research Laboratory, Airbase Technologies Division (AFRL/MLQ—Tyndall AFB, Florida). As the organization primary responsible for project administrative, financial and logistical management, AFRL/MLQ and, in particular, Major Michael J. Calidonna and Mr. Paul E. Kerch, are commended for their outstanding performance. The authors wish also to recognize the contributions of Mr. John C. Bosch, Jr., and Mr. Thomas J. Logan from the EPA's Emission Measurement Center (Research Triangle Park, N.C.) for providing invaluable technical and regulatory guidance, without which the success of the DOCS field demonstration would not have been possible. Eastern Technical Associates, Inc. (Garner, N.C.) deserves special thanks for their assistance in collaborating with the DOCS technology evaluation team and for providing exceptionally skilled smoke school equipment operators during Phase I of the field demonstration activities.

Other members of the regulatory and professional consulting community whose support was invaluable to the overall success of the DOCS field demonstration include Mr. Raymond V. Magyar (EPA Region VI), Mr. Richard W. Sprott (Utah Division of Air Quality) and Mr. Erik Haas (HMH Consulting, Inc. Anchorage, Alaska). Department of Defense (DoD) military and civilian personnel whose participation and contributions in serving on the Optical Science Advisory Panel merits special recognition include Major Roger L. Claypoole, Ph.D. (Wright Patterson AFB, Ohio), Dr. Peter L. Marasco (Air Force Institute of Technology) and Dr. Joseph D. Wander (Tyndall AFB).

Members of the Hill AFB, Utah, environmental program whose contributions to the success of the DOCS field demonstration program deserve special acknowledgement include Mr. Steven L. Rasmussen (DOCS program manager), Dr. Daniel A. Stone (senior environmental scientist/chair opacity science advisory panel), Dr. Michael J. McFarland (quality assurance/data quality objectives) and Mr. Josh Gunter (DOCS field logistics support contractor). The authors would like to thank the many DoD military and civilian personnel who voluntarily participated in the DOCS field data collection efforts and digital image readings at various facilities within the states of Alaska, Georgia, Ohio and Utah.

Finally, it should be noted that all results from the DOCS field demonstration were published in the following peer-reviewed scientific journals: 1) McFarland, M.J., Stone, D.A., Calidonna, M. J., Rasmussen, S.L., and S. H. Terry (2003) "Evaluation of the Digital Opacity Compliance System (DOCS) in High Mountain Desert Environments" *Journal of the Air and Waste Management Association* vol. 53, pp. 724–730, 2) McFarland, M. J., Stone, D.A., Calidonna, M.J., Kerch, P.E., Rasmussen, S. L. and S. H. Terry, (2004) "Measuring Visual Opacity Using

Digital Imaging Technology" *Journal of Air and Waste Management Association* vol. 54, pp. 296–306 and 3) McFarland, M. J., Stone, D.A., Rasmussen, S. L., Calidonna, M.J., Kerch, P.E., and J. A. Gunter (2004) "Evaluation of the Digital Opacity Compliance System (DOCS) at Military and Commercial Industrial Sites" *Federal Facilities Environmental Journal* vol. 15, Issue 2, pp. 73–81.

Abstract

Results from technology field tests of the Digital Opacity Compliance System (DOCS) confirmed that, under fair weather conditions (*i.e.*, clear sky conditions), the DOCS technology consistently met the quantitative performance standards for accuracy and reliability defined for a successful demonstration. In the field application of the DOCS technology at real-world industrial operations, the DOCS accuracy in measuring visual opacity was not only comparable to Method-9-certified human observers but the DOCS technology exhibited several important practical advantages for DoD facilities including 1) improved measurement objectivity and reliability, 2) lower deployment and maintenance costs and 3) generation of a permanent digital image of visible opacity that can be easily referenced in challenging regulatory enforcement actions. These findings further support the developer's claim that the DOCS technology is a more reliable opacity measurement method than Method-9-certified human opacity readers for all types of stationary sources and under all weather conditions.

Under adverse weather conditions (*e.g.*, dark overcast skies), the accuracy of *both* the DOCS technology and Method-9-certified human opacity readers in measuring visible opacity was diminished. However, under all weather conditions, the variability in the DOCS opacity measurements was significantly *less* than Method 9, which supports the claim that the DOCS technology is consistently more reliable than Method 9.

Economic analysis of the DOCS technology illustrated that stateside and remotely located DoD facilities could recognize an *annual* cost savings of $9,011.82 and $15,650.10, respectively, *per pair* of trained technology users. Given the fact that DoD currently certifies over 3,400 individuals trained in Method 9, DoD-wide adoption of the DOCS technology has the potential of saving the DoD in excess of *15.3 million dollars annually* in compliance costs. With these potential cost savings, the payback period for investment in the DOCS technology is *less than one year*. Using a net present value (NPV) analysis, evaluation of the life-cycle cost savings demonstrated that DoD stateside and remotely located facilities could potentially save $40,118.82 and $69,671.12, respectively, *per pair* of trained technology users at a facility. These costs savings translate to a potential aggregate financial benefit to DoD of at least *$68.2 million dollars* over the life-cycle of the DOCS equipment (assuming a useful life of five years).

Finally, the overarching factor that affects technology costs as well as future technology development is regulatory approval of a digital camera-based visible opacity measurement method. The future of the DOCS technology and all other digital-camera based opacity measurement technologies is highly sensitive to the development and promulgation of an EPA-approved test method for digital-camera-based opacity verification. Without such regulatory approval, the opportunity for the DOCS or similar technology to be supported within the marketplace is nonexistent.

1. Introduction

1.1 Background

Most US Department of Defense (DoD) installations/facilities located in the United States are subject to Title V of the 1990 Clean Air Act Amendments. While there are a variety of air sources regulated under Title V, the most common are those that generate visible emissions, *e.g.*, power plants, emergency generators, etc. [2]. While some large sources employ dedicated equipment to measure and record visible opacity within a stack (*e.g.*, continuous opacity monitors or COMs), these systems are expensive to purchase and maintain. For the majority of regulated air sources, the primary method for determining compliance with permitted opacity levels is the US Environmental Protection Agency's (EPA's) Reference Method 9 (Method 9). Method 9 relies on trained human observers to visually determine compliance by estimating the opacity of a smoke plume once every 15 seconds for a specified period (Table 1-1).

Table 1-1 EPA Reference Method 9 Field Procedures

Positioning

- Observer must stand at a distance sufficient to provide a clear view of the visible emissions
- Observer must have the sun oriented within a 140° sector to the back of the observer
- Observer must ensure that the line of vision is perpendicular to plume flow direction

Recording

- Observer must record name of the facility, emission location, facility type, observer's name and affiliation, and the date on which observations are made.
- Observer must record time, estimated distances to the emission location, approximate wind direction and speed, description of sky conditions and plume background at the time of measurement.

Observations

- Observer must make opacity observations at the point of greatest visible opacity where condensed water vapor is absent.
- Observer must observe plume at 15-second intervals. Observer must not look continuously at the plume.
- Observer must record approximate distance from outlet to point in plume where observations were made.
- Observer must record opacity observations to the nearest 5% opacity at 15-second intervals on an observational record sheet (at least 24 observations must be recorded).

Data Reduction

- Observer shall determine opacity as an average of 24 consecutive observations recorded at 15-second intervals.

The 15-second opacity recordings are then averaged to determine a single opacity estimate that is compared against the facility's permitted opacity level to demonstrate compliance [2, 3]. If the appropriate field procedures are followed, a Method-9-certified individual is legally authorized to measure and report the opacity compliance status of a regulated source (Appendix C).

To become legally certified as a Method 9 visual opacity observer, an individual must complete both classroom training and a visual opacity field examination at an EPA-approved smoke school once every six months. The field examination requires that the Method 9 candidate estimate the visual opacity of 25 white and 25 black smoke plumes with an error rate of no greater than 15% for any individual opacity observation and an aggregate opacity estimation error rate of no greater than 7.5% for all fifty (50) readings [4]. While Method 9 has an extensive history of successful employment, its opacity estimates are inherently subjective and completing the process for achieving certification can be expensive. In other words, since Method 9 relies on human observation, it is vulnerable to claims of inaccuracy, bias and, in some cases, outright fraud.

The Digital Opacity Compliance System (DOCS), which is an innovative technology that employs digital imaging technology for quantifying visible opacity, has been developed and field tested as a technically defensible and economically competitive alternative to Method 9. The DOCS uses a commercial-off-the-shelf (COTS) digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using statistical computer software. The DOCS technology has been advertised as not only an accurate and reliable alternative technology to Method 9 for quantifying opacity, but it has the added advantage of furnishing the technology user a permanent, visual record of the emissions [5, 6].

1.2 Objectives of the Demonstration

The objective of the present demonstration was to evaluate the technical field performance of the Digital Opacity Compliance System (DOCS), a technology that has been proposed as a potential cost-effective alternative to Method 9 for measuring opacity. The DOCS technology uses a commercial-off-the-shelf (COTS) digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using statistical computer software.

The current field demonstration was conducted in two phases. Phase I focused on the evaluation of the DOCS technology at three (3) EPA-approved Method 9 smoke schools located in various geographical areas including Ogden, Utah; Augusta, Georgia; and Columbus, Ohio. The goal of Phase I was to determine the ability of the DOCS technology to achieve the Method 9 accuracy performance standard under the same set of field test conditions under which human observers were evaluated. Phase II of the field demonstration sought to broaden the technology evaluation conditions to include comparison of the DOCS technology with Method-9-certified human observers in estimating the opacity of air emissions associated with regulated processes at various DoD industrial and commercial facilities.

Field demonstration results confirmed that the DOCS technology can accurately measure visible opacity at a fraction of the cost required to employ Method-9-certified observers. The financial advantage (as reflected in annual cost savings) conferred by utilizing the DOCS technology at stateside and remotely located DoD facilities amounted to $9,011.82 and $15,650.10,

respectively, *per pair* of trained technology users compared to Method 9. With these potential cost savings, the payback period for investment in the DOCS technology is *less than one year*. Another inherent advantage of the DOCS technology confirmed by the field demonstration results was the significantly improved forensic reliability and reproducibility in capturing visible opacity with digital photographs. The variability in the DOCS technology measurements was found to be significantly less that Method 9 regardless of weather conditions. These findings were not surprising since, unlike Method 9, which depends solely on the visual judgment of opacity by a human observer, the DOCS technology provides objective and reproducible data. The digital photograph, which may be re-examined at any time, represents a visual archive of the emissions as it existed at the time in question. In fact, the over 10,000 digital photographs evaluated in the DOCS field demonstration study are currently stored and available on compact discs and can be reviewed by any interested third party, if requested.

Finally, with respect to regulatory standards attained, field demonstration results confirmed that the DOCS can measure visible opacity of regulated stationary sources under favorable weather conditions with an accuracy that is significantly greater than the codified Method 9 accuracy standard of ±7.5%. Moreover, within the typical range of permitted regulatory opacity (*i.e.*, 0 to 40 % opacity), the measurement accuracy of the DOCS technology was comparable to that achieved by Method-9-certified human observers.

1.3 Regulatory Drivers

Compliance with a visual opacity standard is the most common air quality requirement found in a facility's Title V operating permit [3]. Although there is limited use of continuous opacity monitors (COMs) within regulated DoD facilities, Method 9 is by far the most commonly prescribed method for estimating visual opacity. Since the ultimate goal of the current field demonstration is to receive regulatory approval for the use of the DOCS technology by regulated DoD facilities, the EPA's Emission Measurement Center (EMC) in Research Triangle Park, N.C., as well as a number of Method 9 experts from EPA regional offices including EPA Region VI (Texas) and EPA Region VIII (Colorado) were included as partners in the current study. In addition to the federal environmental scientists and regulators who participated in the planning and implementation of the DOCS technology field demonstration activities, air quality regulators from the states of Alaska, Texas and Utah provided valuable technical and regulatory insight into the limitations of Method 9.

1.4 Stakeholder/End-User Issues

The use of the DOCS technology will benefit all regulated DoD facilities in verifying compliance with permitted visible opacity limits. The improved objectivity in quantifying visible opacity levels (relative to the use of Method 9) through the use of digital imagery will provide DoD compliance personnel with a superior method in documenting their facility's compliance status. The digital photographs of opacity, which may be used independently (once the technology receives regulatory approval) or in conjunction with Method 9 human observations for regulatory reporting purposes, may be analyzed by regulators to certify a regulatory facility as compliant. Finally, the environment, in general, will improve through the use of the DOCS technology because it confers to industrial facilities the ability to rapidly evaluate and adjust their process operating conditions to reduce visible air emissions.

2. Technology Description

2.1 Technology Development and Application

Prior to the current field demonstration, the DOCS technology was evaluated at both an EPA-approved smoke school and at a limited number of industrial sites [5]. Air quality inspectors employed at Hill Air Force Base, Utah (Hill AFB), have been employing the DOCS technology to monitor the visible opacity associated with regulated air sources since November 1999. Because of its early and notable success at Hill AFB, the DOCS technology is identified by the State of Utah Division of Air Quality (UDAQ) as an allowable opacity measurement option available within the Hill AFB Title V operating permit. Hill AFB compliance personnel together with UDAQ are convinced of the technical and economic advantages in using the DOCS technology for opacity determination and are fully committed to its future use. The chronological history of the DOCS technology development and funding support are summarized in Table 2-1.

Table 2-1 Early History of DOCS Development

- Feasibility Study sponsored by SCIENTECH, Inc., which provided $10,000 to Utah State University's Space Dynamics Laboratory (SDL), was focused on evaluating the general concept of employing digital imagery for visible opacity estimation.

- DOCS concept development and demonstration were conducted by SDL under a grant funded though the National Aeronautical and Space Administration (NASA) Stennis Research Center's Affiliated Research Center Program. NASA funds (*ca.* $80,000) were provided directly to the SDL to support both staff and graduate student involvement during an eight-month effort.

- Funds to support the DOCS prototype development and evaluation of opacity estimation algorithms were provided by the US Air Force under the 3600 program.

- Tyndall Air Force Base, Florida, in collaboration with Hill Air Force Base, Utah, began preliminary field testing of DOCS, which included the purchase and application of several DOCS systems and licenses. The cost of the field-testing demonstration was approximately $32,500.

- SCIENTECH, Inc., invested approximately $25,000 in completing the development of the DOCS analysis algorithms and finishing the DOCS graphic user interface (GUI) and report generator.

- The State of Utah's Division of Air Quality (UDAQ) purchased one DOCS camera and software license for field application in February 2000 at a cost of $5,000 and Hill AFB purchased four additional DOCS cameras and software licenses in addition to their original site license for $8,000.

The use of digital image processing represents a unique and innovative approach for certifying regulatory compliance with visual opacity standards. Other than the Method-9-certified human observer, the only competing technology in use today requires air emission sampling using permanently installed continuous opacity monitors (COMs). COMs have no portability and are costly both to purchase and maintain. Digital image processing, on the other hand, is completely portable and the analysis can be done either on site, using a standard notebook computer, or later in the office, using a common desktop system. Figure 2-1 depicts how the DOCS technology conceptually manages digital imagery data to estimate the opacity associated with fugitive dusts as well as the opacity associated with emissions from stationary sources. In all cases, the digital images can be archived by storing them on computer media and opacity analysis can be conducted at any time, an advantage obviously denied to the Method-9-certified human observer.

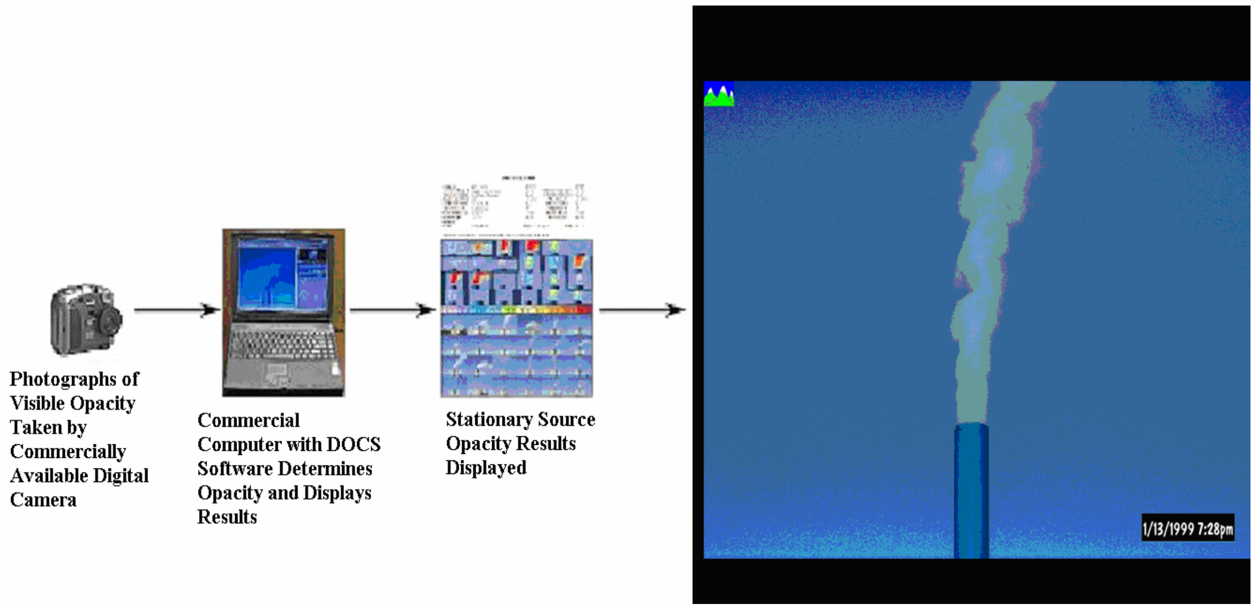

Figure 2-1 Schematic of DOCS Technology

In the field application of the DOCS technology to measure opacity associated with stationary sources, digital photographs of visible emissions are taken from valid positions according to codified Method 9 specifications. Once downloaded to a computer on which the DOCS computer software has been installed, the digital images can be evaluated for visible opacity. The process for analyzing the digital image for opacity include the following steps: 1) activating the DOCS opacity computer program, 2) retrieving those digital photographs that are to be evaluated for visible opacity and 3) using the computer program to draw an analysis box (or grid) around that portion of the visible emissions that will be analyzed (Figure 2-2).

After the computer software selects the purity of color (*i.e.*, saturation) that best corresponds to the background, the opacity of the image is calculated based on the optical properties of the pixels contained in the analysis box. The size and shape of the analysis box, which is controlled by the user of the software, must be chosen judiciously since the final opacity measurement will ultimately depend on what part of the image the DOCS computer software identifies as background.

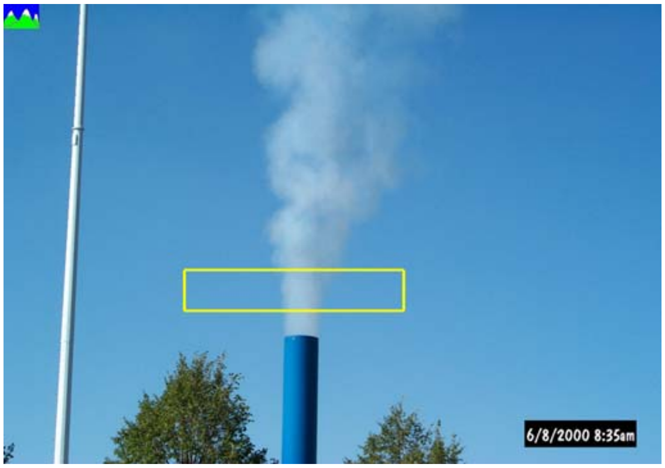

Figure 2-2 Use of the DOCS Software - Drawing the Opacity Analysis Box

2.2 Previous Testing of the Technology

Since 1999, the DOCS technology has undergone a number of successful field demonstrations at Hill Air Force Base, Utah. These field demonstrations have included evaluation of the DOCS technology to quantify the opacity associated with both regulated stationary air sources as well as fugitive dust from range maintenance activities [5]. Prior to the collection of any field data in support of the present DOCS field demonstration, an expert Opacity Science Advisory Panel consisting of experienced scientists and engineers from DoD, EPA and academia was established to conduct a comprehensive review of the science that supported the DOCS computer program development (Table 2-2). Panel members were selected based on their demonstrated expertise in digital computer-based algorithm processing, measurement of opacity and smokes, visibility determination and modeling, or statistical experimental design. After reporting that the fundamental principles that supported the DOCS technology were scientifically defensible, the panel provided additional review and comment on the DOCS technology field demonstration protocol, statistical analysis methods, demonstration study conclusions and recommendations.

2.3 Factors Affecting Cost and Performance

The overarching factor that affects technology costs is regulatory approval of the digital camera-based visible opacity measurement method. The future of the DOCS technology and all other digital-camera-based opacity measurement technologies is highly sensitive to the development and promulgation of an EPA-approved digital-camera-based opacity-verification test method. Without such regulatory approval, the opportunity for the DOCS or similar technology to reach the marketplace is nonexistent.

Beyond the financial impact stemming from regulatory approval of the DOCS, better-quality and lower-cost digital equipment is continuously being introduced into the marketplace. The employment of digital cameras equipped with higher resolution, faster processing times and/or enhanced zoom capability will allow the DOCS technology to be applied to the measurement of visible opacity associated with mobile sources as well as regulated sources located considerable distances from the observer (*e.g.*, marine vessels).

Another factor that will impact cost and performance is the enhanced efficiency of the DOCS technology training program. Unlike Method 9, DOCS technology training can be completely computerized and made available over the web or through the development and distribution of a training CD. By utilizing standard information technology (IT) tools, the DOCS technology training program can be designed to minimize, if not eliminate, the need to budget travel expenses or hire temporary workers in support of a DoD visible opacity compliance program. It is anticipated that, if the DOCS technology can be supported to take full advantage of new scientific and technical developments in digital imagery and/or information technology, the DOCS technology user costs should continue to decrease.

2.4 Advantages and Limitations of the Technology

Advantages for the DOCS technology fall into two distinct categories. The first category is economic and, through performing a simple cost analysis, it has become patently clear that the DOCS technology has the potential of saving the DoD considerable financial and personnel resources. The reduction in compliance costs associated with the implementation of the DOCS technology stems primarily from the fact that the type of training necessary to support a digital camera-based opacity method can be furnished through a web-based or CD-type program at the technology user's facility. A computer-based training program minimizes worker productivity loss as well as eliminates the travel costs associated with supporting Method 9 smoke school training. Moreover, a web-based or CD-type training program can be completed in a fraction of the time (normally four to eight hours) needed to support Method 9 certification (three days).

The second category of advantages associated with the DOCS technology includes improved forensic reliability and reproducibility. Method 9 depends exclusively on the visual judgment of opacity [7, 8]. The visual observer records his observation on a form and, if needed, that form and that individual may be required to provide expert testimony if legal enforcement action is pursued. The expert testimony then becomes merely an individual's affirmation that the documented opacity is what the observer recorded on that day. Because it depends on human judgment, Method 9 is inherently subjective and, therefore, is vulnerable to claims of bias, inaccuracy or outright fraud. Alternatively, the DOCS technology provides objective, reproducible and reliable data. The digital photograph of opacity is a visual archive of the emissions as it existed at the time in question. The digital photograph may be re-examined at any time to establish a regulated source's opacity level.

Technical limitations associated with the DOCS technology are similar to those encountered by a Method-9-certified opacity observer. Current regulations governing the measurement of visual opacity place physical constraints on the angle of the observation with respect to the sun and the distance to the stack [2, 4, 8]. To effectively demonstrate DOCS equivalency to Method 9, the DOCS technology must be subjected to these same constraints. With respect to background sky conditions, the DOCS technology field demonstration results confirmed that Method-9-certified observers have significant difficulty in accurately measuring the opacity of smoke plumes when sky conditions are characterized as overcast or otherwise highly variable. Like Method-9-certified human observers, DOCS has similar limitations in that the technology performs best during clear blue sky days [6, 8].

3. Demonstration Design

3.1 Performance Objectives

The overarching objective of the technology field demonstration was to evaluate whether the ability of the DOCS technology to measure opacity was equivalent to Method 9. Because of the intent to petition federal regulators to approve the use of the DOCS technology in lieu of Method 9, the EPA's Emissions Measurement Center (EMC) was invited to become an active participant in the field demonstration program. EMC involvement in the field demonstration activities was integral in assessing both the scientific underpinnings of the DOCS technology as well as the regulatory hurdles associated with the use of a digital-camera-based opacity technology by the regulated community. Table 3-1 describes the performance criteria and metrics used to characterize the equivalency of DOCS to Method 9.

Table 3-1 Performance Metrics Used to Establish DOCS Performance

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	1. Determine the statistical equivalency of the DOCS to EPA Method 9	Demonstrate that the DOCS opacity measurements are statistically within the Method 9 acceptable margin of error (*i.e.*, ± 7.5%) at the 99% confidence level .	Yes. Under fair weather conditions, the DOCS technology was able to quantify visible opacity within the Method 9 acceptable margin of error at the 99% confidence level.
	2. Estimate reliability of the DOCS relative to EPA Method 9 human observers	Compare the statistical variability (*i.e.*, 99% confidence interval) of the mean difference in opacity readings reported by the DOCS to the statistical variability (*i.e.*, 99% confidence interval) of the mean opacity differences reported by recently certified smoke readers.	Yes. The width of the 99% confidence about the mean opacity difference was smaller for DOCS than for Method-9-certified human observers under all weather conditions indicating that the DOCS is less variable (*i.e.*, more reliable)
Qualitative	1. Reproducible results 2. Near real-time monitoring	Digital record Increase observations	Yes. Digital photographs of opacity were used to generate reproducible results.

3.2 Selecting Test Sites/Facilities

Field demonstration sites were selected through extensive discussion between the EPA's Emission Measurement Center (EMC) and the Opacity Science Advisory Panel (Table 2-2). During Phase I of the field demonstration program, identified sites were selected based on their geographic location and the need to include field demonstration sites whose weather patterns were representative of the climates of the Southeast, Midwest, and Western United States (US). Following completion of Phase I, the DOCS technology was evaluated at various DoD industrial and commercial test sites where there was an acknowledged and urgent need for a digital camera-based opacity measurement method (Phase II). Through discussions with the EPA's Emission Measurement Center (EMC), EPA Region X and that State of Alaska Division of Air Quality, the Phase II DOCS field demonstration activities were limited to those DoD industrial and commercial sites located in the State of Alaska. Data collected during Phase II reflected the performance of the DOCS technology under "real-world' industrial conditions in an environment that was typical of Pacific Northwest climates.

3.3 Test Facility History/Characteristics

The DOCS Phase I field demonstration sites for the Method 9 smoke school validation activities included the cities of Ogden, Utah, Augusta, Georgia, and Columbus, Ohio. The EPA's Emission Measurement Center recommended that the DOCS technology should be evaluated at those EPA-approved Method 9 smoke schools conducted by Eastern Technical Associates (ETA, Garner, North Carolina). ETA currently conducts more than 80% of the smoke schools within the United States and there was an established, professional working relationship between the EPA's Emission Measurement Center and ETA [8]. The following sections summarize the filed demonstration test sites in greater detail.

3.3.1 Ogden, Utah, Smoke School

Hill Air Force Base, Utah (Hill AFB), is home to the Ogden Air Logistics Center, which is located in Utah's Davis and Weber counties. Hill AFB is located at approximately 4500 feet above sea level and its normal weather patterns are typical of a high mountain desert climate. Hill AFB operates a number of process boilers to supply heat and process steam to on-base facilities. The Utah Division of Air Quality (UDAQ) has established a regulatory limit for Hill AFB boilers of 20% visible opacity. Although Hill AFB utilizes Method 9 as its primary opacity compliance certification method, the DOCS system has been employed at Hill AFB since 1999 as an opacity monitoring technology for a range of industrial process operations, including boilers. Because of its successful deployment at Hill AFB, UDAQ has permitted the inclusion of the DOCS technology within Hill AFB's Title V operating permit as a valid method with which to certify opacity compliance.

As part of the current DOCS field demonstration activity, the DOCS technology was evaluated at an ETA sponsored smoke school conducted at Weber State University (located in Ogden, Utah) from October 2 through October 4, 2001. Weber State University is located approximately 6.5 miles from Hill AFB and, like Hill AFB, its weather conditions were assumed to reflect those found in high mountain desert climates.

3.3.2 Augusta, Georgia, Smoke School

Fort Stewart, Georgia, is the largest US Army installation east of the Mississippi River and is home to the 3rd Mechanized Infantry Division. Early in the site demonstration selection process, Fort Stewart expressed an interest in using the DOCS technology as a backup opacity measurement method for its boiler stack continuous opacity monitoring (COM) system. To provide the Fort Stewart environmental personnel with DOCS performance data under climatic conditions similar to that found at the facility, it was decided to evaluate the DOCS technology at an ETA-sponsored Method 9 smoke school located in Augusta, Georgia. The smoke school field demonstration, which was held October 30, 2001, through November 2, 2001, generated DOCS performance data under climatic conditions that were assumed to be representative of those found at DoD facilities located throughout the Southeast United States, which would include Fort Stewart, Georgia, among many others.

3.3.3 Columbus, Ohio, Smoke School

Wright-Patterson Air Force Base, Ohio (WPAFB), is the largest, most diverse and organizationally complex facility within the US Air Force. WPAFB, which is home to more than 60 different military units representing a host of Air Force and DoD organizations, is located near Dayton, Ohio. WPAFB operates two large central heating plants that provide heat and process steam to many on-base facilities. As at Fort Stewart, Georgia, WPAFB's environmental management personnel expressed a strong interest in utilizing the DOCS as a backup opacity measurement method in support of their COM units. To document the DOCS technology's performance under climatic conditions representative of those experienced at WPAFB, the field demonstration sites included taking DOCS opacity measurements at an ETA-sponsored Method 9 smoke school located in Columbus, Ohio, from March 26 through March 28, 2002.

3.3.4 Technology Demonstration at DoD Industrial and Commercial Facilities

Phase II of the field demonstration sought to broaden the technology evaluation conditions to include a comparison of the DOCS performance with Method-9-certified human observers estimating the opacity of air emissions associated with regulated processes at regulated industrial facilities. During the process of identifying potential Phase II field demonstration sites, EPA's Emission Measurement Center indicated to the DOCS technology evaluation team that several DoD and commercial facilities within the State of Alaska had requested regulatory approval for the use of the digital camera-based opacity technology at their facilities. The primary interest of these facilities (many of which were located in remote regions) in adopting a digital-camera-based opacity-measurement technology stemmed from the significant and recurring financial costs associated with achieving and maintaining Method 9 certification.

Through discussions among the EPA's Emission Measurement Center, Opacity Science Advisory Board, EPA Region X, State of Alaska Department of Environmental Quality and HMH Consulting (Anchorage, Alaska), it was determined that evaluating the visible opacity associated with the emissions from the following regulated industrial activities in Alaska would represent a valuable test for the DOCS technology: 1) waste incinerator in Anchorage, 2) EPA-approved smoke generator in Anchorage, 3) coal-fired power plant in Healy, 4) coal-fired boiler at Eielson AFB, and 5) diesel-fired pump station in Fairbanks. During the first week of September 2002, the visible emissions from each of these field demonstration sites were evaluated using the DOCS technology.

3.4 Present Operations

At all DoD industrial and commercial facilities at which the DOCS technology was evaluated, Method 9 was employed as either the primary or secondary visual opacity measurement approach. For those industrial facilities at which Method 9 was identified as a secondary approach for measuring visible opacity, the facility had installed a continuous emission monitor (COM) within the air emission stack. Under normal conditions, regulatory permits require that a back-up opacity measurement system be available when the COM is malfunctioning or is otherwise inoperable.

3.5 Pre-Demonstration Testing and Analysis

During Phase I of the field demonstration, the DOCS technology was employed to estimate the opacity of visible emissions generated from a 15-foot stack operated by an EPA-approved Method 9 smoke school certification contractor. Under these test conditions, the ground-truthing of various black and white smoke plume opacities was achieved through the use of an in-line EPA-certified transmissometer. Prior to becoming EPA-certified, the transmissometer underwent a series of performance tests that ensured that the instrument response was consistently within a specified tolerance [2, 4, 7, 8]. During the evaluation of the Phase I field demonstration results, transmissometer opacity readings were subsequently compared to those recorded by the DOCS technology.

Phase II of the field demonstration was designed to evaluate the performance of the DOCS technology against the ability of Method-9-certified smoke readers (*i.e.*, human observers) in measuring the opacity of plumes generated from stacks associated with various industrial operations. It was confirmed before the start of the DOCS technology field demonstration activities that each individual human opacity reader had an active Method 9 certification. To qualify as a Method-9-certified opacity reader, an individual must complete both classroom training and a visual opacity field examination at an EPA-approved smoke school once every six months. The field examination requires that the Method 9 candidate estimate the visual opacity of 25 white and 25 black smoke plumes with an error rate of no greater than 15% for any individual opacity observation and an aggregate opacity estimation error rate of no greater than 7.5% for all fifty (50) readings [8].

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start Up

The DOCS Phase I field demonstration sites for the Method 9 smoke school validation activities included evaluation of the technology at EPA-approved smoke schools conducted in the cities of Ogden, Utah, Augusta, Georgia, and Columbus, Ohio. The EPA's Emission Measurement Center (EMC) recommended that the DOCS technology be tested at Method 9 smoke schools managed by Eastern Technical Associates (ETA, Garner, North Carolina). ETA currently conducts more than 80% of the smoke schools within the United States and its long-term professional working relationship with EMC provided a high level of confidence in the accuracy of field results.

During Phase I, four (4) commercial-off-the-shelf (COTS) digital cameras (*e.g.*, Kodak DC290 or Kodak DC265) were employed to photograph visible emissions generated during the EPA-approved Method 9 certification field test. The DOCS photographic imaging software was

installed and tested on each of the cameras before any photographs were taken. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS photographic imaging software. The loading and activation of the DOCS camera software ensured that all of the digital camera's optical settings were appropriately set to collect photographs that could be subsequently analyzed by the DOCS computer algorithms.

Once the Kodak DC290 or Kodak DC265 digital cameras were loaded with the DOCS camera software, each was hand carried to the smoke school test site. Each camera was positioned on a tripod to provide a clear view of the visible emissions. The minimum distance of the cameras from the stack was equivalent to at least three (3) stack heights (or 45 feet in the present study) with the sun oriented in the 140-degree sector to the back of the camera/observer (Figure 3-1). These field procedures were adopted to be consistent with the published requirements for valid Method 9 visible emissions opacity measurements [8].

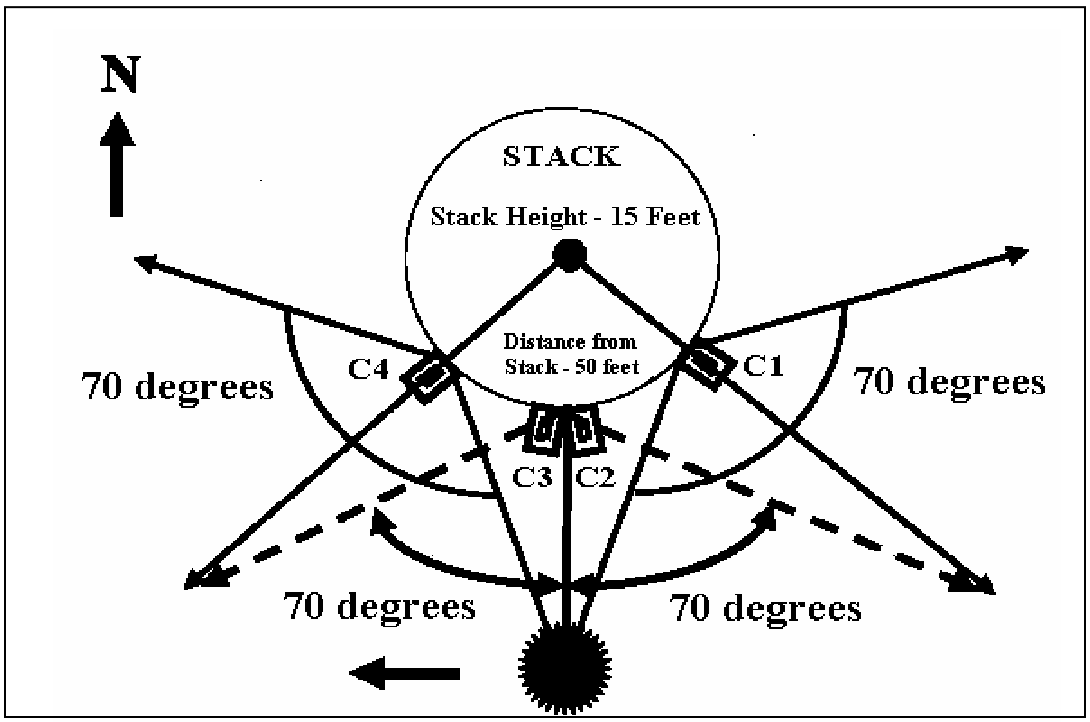

Figure 3-1 Positioning of the DOCS digital cameras, C1, C2, C3, and C4 and visual observers during the smoke school Phase I DOCS field demonstration.

Note that, as the sun moves across the sky, both the camera and visual observers must shift their positions to maintain compliance with the Method 9 opacity observation requirements.

Phase II of the field demonstration sought to broaden the technology evaluation conditions to include a comparison of the DOCS performance with Method-9-certified human observers in estimating the opacity of air emissions associated with regulated processes at regulated industrial facilities. A list and description of each of the DOCS technology Phase II field demonstration sites is proved in Table 3-2.

Table 3-2 Description of DOCS Technology Phase II Field Test Sites

1. The Anchorage Water and Wastewater Sludge Incinerator: At this field demonstration site smoke readings were taken against a gray background sky. Smoke plumes were generated by incineration of municipal water and wastewater treatment sludge.

2. The Golden Valley Electric Power Station #1: This demonstration site provided an opportunity to measure coal-fired combustor systems (black smoke) against a variable sky background.

3. The Alyeska Pipeline Incinerator: The Alyeska pipeline incinerator was barely able to generate any visible smoke and was unable to sustain any high opacity greater than 20% for more than a minute or two.

4. The Eielson Coal-Fired Boiler Plant: The Eielson coal-fired boilers were also unable to generate visible smoke for more than very short periods of time. The opacity that was generated from this facility was read by both DOCS and certified human observers against a background characterized by overcast skies.

5. The Williams North Pole Refinery: Like the previous facilities, the opacities generated from this facility were limited to the low range (0 to 20%) and were read against a background characterized by overcast grey skies and light precipitation.

3.6.2 Period of Operation

The DOCS field demonstration tests were divided into two phases. Table 3-3 summarizes the dates and duration of each phase of the DOCS technology field demonstration.

3.6.3 Operating Parameters for the Technology

During the field study, four (4) commercially available digital cameras (*e.g.*, Kodak DC290 or Kodak DC265) were employed to photograph visible emissions generated as part of the EPA Reference Method 9 certification smoke school. The DOCS photographic imaging software was installed and tested on each of the cameras before any photographs were taken. Use of the DOCS camera software is a security requirement that essentially guarantees that the digital photograph cannot be altered prior to an opacity determination. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS photographic imaging software.

Each camera was positioned on a tripod to provide a clear view of the visible emissions. The minimum distance of the cameras from the stack was equivalent to at least three (3) stack heights with the sun oriented in the 140-degree sector to the back of the camera/observer. These field procedures were adopted to be consistent with the published requirements for valid EPA Reference Method 9 visible emissions opacity measurements.

Digital photographs taken during each day of the DOCS technology field demonstration were collected on one (1) 128-megabyte (128-MB) memory card. Following completion of each day of testing, the memory cards containing digital opacity photographs were removed from the cameras, placed in a labeled container, and stored in a secure location. To minimize the potential loss of opacity data, memory cards were removed from the digital cameras only after the digital camera's power had been turned off. A new 128-MB memory card was then inserted into each camera for completion of the following day's field activities. Digital photographs from the memory cards used during field measurements were downloaded daily to a laptop computer for subsequent opacity analysis.

Table 3-3 Summary of Activities Supporting the DOCS Field Demonstration

Phase	Activity	Location	Dates	Days
I	Opacity Science Advisory Panel (OSAP) Meeting	Ogden, Utah	April 2–4, 2001	3
I	OSAP Meeting	Ogden	June 7–9, 2001	3
I	Utah Smoke School	Ogden	Oct. 2–4, 2001	4
I	OSAP Meeting	Washington, D.C.	Nov. 7–8, 2001	3
I	Manuscript Report Summarizing Utah Smoke School Results	Ogden	Jan.–March 2002	60
I	Georgia Smoke School	Augusta, Georgia	Oct. 30–Nov. 1, 2001	4
I	Ohio Smoke School	Columbus, Ohio	March 26-28, 2002	4
I	OSAP Meeting	Ogden	May 15–17, 2001	4
I	Manuscript Report Summarizing all Phase I Results	Ogden	May–July 2002	60
II	Anchorage Water and Wastewater Sludge Incinerator	Anchorage, Alaska	Sept. 2–7, 2002	1
II	Golden Valley Electric Power Station #1	Healy, Alaska	Sept. 2–7, 2002	1
II	Alyeska Pipeline Incinerator	Healy	Sept. 2–7, 2002	1
II	Eielson Coal-Fired Boiler Plant	Fairbanks, Alaska	Sept. 2–7, 2002	1
II	Williams North Pole Refinery	Fairbanks	Sept. 2–7, 2002	1
II	OSAP Meeting	Washington, D.C.	Dec. 4–6, 2002	3
II	Manuscript Report Summarizing all Phase II Results	Ogden	Dec. 2002–March 2003	60
I&II	Initial Draft of Final Report	Tyndall AFB, Fla.	May–Oct. 2003	120
I&II	Regulatory Project Meeting: EPA EMC; EPA Regions VI and VIII; states of Alaska, Georgia, Ohio, and Utah; DoD (Air Force, Army)	Research Triangle Park, N.C.	June 16–18, 2003	3
I&II	Draft Cost & Performance Report	Tyndall AFB	Nov. 2003–March 2004	120
I&II	Revised Final Report	Hill AFB (Ogden)	Dec. 2004–Feb. 2005	60
I&II	Revised Cost & Performance Report	Hill AFB (Ogden)	Dec. 2004–Feb. 2005	60

3.6.4 Experimental Design

In both Phase I and II of the DOCS field demonstration, the technology was limited to the estimation of visible opacity associated with smoke plumes from stationary air sources. The smoke plumes were generated through either an EPA-approved Method-9-certification smoke generator (Phase I) or a real-world DoD industrial or commercial process operation (Phase II).

Following completion of both phases of the field demonstration data collection activities, the opacity of each smoke plume captured as a digital image was estimated using the DOCS technology computer software by an eight-member panel consisting of federal government civilian personnel, US military personnel and federal government contractors. Each panel member was provided a compact disc that contained all of the digital photographs taken from the respective smoke school as well as the DOCS computer software and user guide. The panel members were required to work independently to estimate the plume opacity of each digital photograph using the furnished computer software. Once panel members had completed their analyses, the opacity results were transferred and stored electronically in a relational database for subsequent statistical evaluation. An independent quality control officer was assigned the responsibility of maintaining the integrity of all opacity data.

The following section provides a brief summary of the experimental field design including 1) the data quality objectives, 2) brief description of the EPA-approved smoke schools and 3) DoD industrial or commercial process operations. Additional details of the experimental design are provided in Section 3.3 of the current report.

3.6.4.1 *Data Quality Objectives*

One of the most effective approaches for developing a statistically defensible data collection activity is the US Environmental Protection Agency's (EPA) Data Quality Objectives or DQO process [9]. The DQO process provides the environmental decision-maker with a systematic method for defining the data quality criteria that a compliance-sampling plan should satisfy. The data collection elements for which specific data quality criteria are defined by the DQO process include the following: 1) when and where to collect samples and 2) the minimum number of monitoring samples needed to support a claim of regulatory compliance with a known level of confidence. The current field demonstration project used the EPA's DQO process for evaluating alternatives to Method 9 (Appendix B).

3.6.4.2 *Ogden, Utah, Smoke School*

As part of the DOCS technology field demonstration activity, the DOCS technology was evaluated at an ETA-sponsored smoke school conducted at Weber State University (located in Ogden, Utah) in October 2001. Weber State University is located approximately 6.5 miles from Hill AFB and, like Hill AFB, its weather conditions were assumed to reflect those found in high mountain desert climates. Additional details of the Phase I experimental design are provided in Section 3.6.1 of this report.

3.6.4.3 *Augusta, Georgia, Smoke School*

Fort Stewart, Georgia is the largest US Army installation east of the Mississippi River and is home to the 3rd Mechanized Infantry Division. To provide the Fort Stewart environmental personnel with DOCS technology performance data under climatic conditions similar to that found at the facility, it was decided to evaluate the technology at an ETA-sponsored Method 9

smoke school located in Augusta, Georgia. These field demonstration tests were conducted from October 30 through November 2, 2001. Additional details of the Phase I experimental design are provided in Section 3.6.1 of this report.

3.6.4.4 *Columbus, Ohio, Smoke School*

As at Fort Stewart, Georgia, environmental management personnel Wright-Patterson Air Force Base, Ohio, expressed a strong interest in utilizing the DOCS technology as a backup opacity measurement method in support of their COM units. To document the performance of the DOCS technology under climatic conditions representative of those experienced at WPAFB, the field demonstration included application of the DOCS technology at an ETA-sponsored Method 9 smoke school located in Columbus, Ohio. These field demonstration tests were conducted March 26–28, 2002. Additional details of the Phase I experimental design are provided in Section 3.6.1 of this report.

3.6.4.5 *DoD Industrial and Commercial Sites*

During Phase II, four (4) COTS digital cameras (*e.g.,* Kodak DC290 or Kodak DC265) were employed to photograph visible emissions generated during the DOCS field demonstration tests. The DOCS commercial digital imaging software was installed and tested on each of the cameras before any photographs were taken. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS camera software.

Rather than assigning digital cameras to fixed positions relative to the sun (*e.g.*, Phase I), the DOCS camera operators were allowed to position themselves in any valid Method 9 location relative to the stack [8]. In addition to the four DOCS camera operators, from six to eight Method-9-certified readers were available at each DoD industrial or commercial site to estimate visible opacity. The Method-9-certified readers consisted of facility personnel as well as members of the DOCS technology evaluation team.

During the field test, the team field coordinator would inform the DOCS camera operators and Method-9-certified readers when to begin evaluating plume opacity. The camera operators and Method-9-certified human observers would then estimate plume opacity once every 30 seconds for a 12-minute period (generating a minimum of 24 readings and photographs per plume).

3.6.5 Demobilization

At the conclusion of Phase I and Phase II DOCS field demonstration, field equipment including the Kodak DC265 or Kodak DC 290 digital cameras were powered off by field technicians according to the manufacturer's instructions and placed back in their storage cases. All environmental monitoring equipment were returned to their storage cases by field technicians at the completion of the Phase I and Phase II DOCS field demonstration. These included the following 1) anemometer, 2) sling psychrometer, 3) Abney Level (sun angle measurement), 4) stop watch and 5) magnetic compass.

3.7 Selection of Analytical/Testing Method

3.7.1 Weather Monitoring

During both Phase I and II DOCS field demonstrations, on-site field personnel recorded the values of specific climatic parameters including: 1) mean air temperature, 2) average wind speed, 3) maximum wind speed, 4) wind direction, 5) sky conditions, 6) relative humidity, 7) visibility, 8) barometric pressure, 9) precipitation, 10) horizontal sun angle and 11) vertical sun angle. Methods used to estimate the value of each climatic parameter are summarized in Table 3-4.

Table 3-4 Methods Used to Estimate the Value of Various Climatic Parameters

Parameter	**Method**
Mean temperature	Standard liquid thermometer (Eastern Technical Associates, Inc.)
Average wind speed	Standard anemometer (Eastern Technical Associates, Inc.)
Maximum wind speed	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Wind direction	Standard anemometer (Eastern Technical Associates, Inc.)
Sky conditions	Visual observation
Relative Humidity	Sling Psychrometer (Eastern Technical Associates, Inc.)
Visibility	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Barometric Pressure	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Precipitation	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Horizontal Sun Angle	Magnetic compass (Eastern Technical Associates, Inc.)
Vertical Sun Angle	Abney level (Eastern Technical Associates, Inc.)

4. Performance Assessment

4.1 Performance Criteria

The specific performance criteria used to evaluate the DOCS technology performance are summarized in Table 4-1. Prior to the collection of any field data, the characteristics of a successful DOCS field demonstration were defined to include the following technology performance criteria: 1) the DOCS technology should achieve the codified Method 9 accuracy level at specified environmental conditions and 2) the variability in the DOCS technology opacity measurements should be demonstrated to be significantly less than what is currently achieved by Method-9-certified human smoke readers. Achievement of these primary technology performance criteria would be necessary to claim a successful DOCS field demonstration. Beyond the primary performance criteria, establishing that the DOCS technology can be operated without degradation in output quality and documenting the level of operational difficulty (ease of use) are important technology performance criteria.

Table 4-1 DOCS Technology Performance Criteria

Performance Criteria	**Description**	**Primary or Secondary**
Validate as an acceptable Alternative to EPA Method 9	Ensure the DOCS opacity measurements are statistically within the acceptable margin of error established for EPA Method 9 certification at the 99% confidence level.	Primary
Validate forensic reliability of system	Process the DOCS technology and certified human observer opacity measurement data and compute the mean difference and the associated 99% confidence intervals.	Primary
Improve the amount of quality data collected	Show the DOCS can operate continuously with no degradation to the quality of output.	Secondary
Ease of use	Show that one trained individual can observe multiple emission sources with one system.	Secondary

4.2 Performance Confirmation Methods

To establish whether the DOCS technology is capable of estimating visible emissions from stationary air pollutant sources as accurately and reliably as EPA Reference Method 9 visible emission observers, opacity measurements recorded by both methods were collected during the field demonstration. During Phase I of the field demonstration, the primary source of data required to evaluate the performance of the DOCS technology consisted of opacity readings recorded simultaneously by 1) an EPA-certified in-line transmissometer, 2) Method-9-certified visible opacity human observers and 3) the DOCS technology. Statistical analysis of the mean difference in opacity measurements generated by comparing the opacity readings recorded by the EPA certified in-line transmissometer and the opacity readings recorded by both the Method-9-certified human observers and the DOCS technology served as the technical basis for comparing

the equivalency of the two technologies. If the DOCS technology estimated visible opacity with an accuracy that was equal to or better than the codified Method 9 accuracy level (*i.e.*, 7.5%) at the 99% confidence level, the conclusion would be that one of the primary performance criteria has been achieved. Similarly, if the width of the 99% confidence interval (99% CI) associated with the DOCS technology measurements were demonstrated to be significantly smaller than the 99% CI associated with the Method-9-certified human opacity observations, the conclusion drawn would be that both primary performance criteria have been met.

During Phase II of the DOCS field demonstration, not all regulated air sources were equipped with in-line transmissometers (*i.e.*, continuous opacity monitors). Without the benefit of a reliable and regulatory approved opacity monitor, a comparison of the accuracy of the DOCS relative to Method-9-certified smoke readers could not be achieved. However, opacity data collected from air sources not equipped with opacity sensors could be used to determine whether the DOCS and Method-9-certified opacity readers yielded field results that were statistically different. Therefore, the opacity data collected at the DoD industrial and commercial sites were analyzed differently, based on whether the DOCS opacity measurements could be verified by a continuous opacity monitor (COM). In other words, for those air sources equipped with COMs, the DOCS field demonstration data were managed in a comparable manor to the data collected during Phase I (*i.e.*, conclusions could be drawn regarding the technology's accuracy). For those air sources not equipped with COMs, a simple comparison of the technology's reliability was conducted.

4.3 Data Analysis, Interpretation and Evaluation

4.3.1 Phase I—Ogden, Utah, Smoke School

During the three (3) days of DOCS field testing at the Ogden, Utah, site, weather conditions were near perfect for measuring visual opacity (*i.e.*, clear blue skies, low wind and low humidity—Table 4-2).

Table 4-2 Climatic Conditions in Ogden, Utah

Parameter	Day of Test		
	Day 1	Day 2	Day 3
Mean Temperature (° F)	66.2	60.8	60.8
Average Wind Speed (mph)	8.9	9.7	8.1
Maximum Wind Speed (mph)	13.8	16.1	11.4
Wind Direction	N-NW	E-SE	S-SE
Sky Conditions	Clear	Clear	Clear
Relative Humidity (percent)	27.2	45.2	30.5
Visibility (miles)	7.0	7.0	7.0
Barometric Pressure (in. of Hg)	30.08	30.11	30.01
Precipitation (in.)	0	0	0
Vertical Sun Angle (degrees)	42.2	39.4	38.5

During the Ogden, Utah, smoke school, approximately 4,741 digital images (2,336 black plumes and 2,405 white plumes) were analyzed for visible opacity using the DOCS computer software. The decision to exclude some images from the DOCS analyses was based on a number of technical problems including 1) physical obstruction of the smoke plume (*e.g.*, trees, clouds, telephone poles, etc.) and 2) folding, twisting or other significant physical disruptions to the plume.

4.3.1.1 *Quantitative Analysis—Ogden, Utah, Smoke School*

The statistical parameters identified as critical in the technical evaluation of DOCS were 1) the absolute value of the mean opacity difference (*e.g.*, opacity measurement recorded by DOCS minus the opacity measurement reported by the EPA-approved transmissometer) and 2) 99% confidence interval of the mean opacity difference. Table 4-3 summarizes the statistical results from the Ogden, Utah, field trial of the DOCS.

Table 4-3 Statistical Data Summary of Ogden, Utah, Smoke School DOCS Evaluation

Color of Smoke—Opacity Measurement Approacl	Opacity Range (%)	Mean Difference (%)	Number of Samples	99% CI[1]
Black—DOCS[3]	0–100	6.4	2336	6.0–6.8
Black—certified observers	0–100	6.7	246	5.4–8.1
Black—DOCS	0–60	5.6	1957	5.2–6.0
Black—certified observers	0–60	5.4	212	4.1–6.8
Black—DOCS	0–40	5.4	1745	4.9–5.8
Black—certified observers	0–40	4.8	194	3.5–6.1
White—DOCS	0–100	10.0	2405	9.4–10.6
White—certified observers	0–100	8.5	282	7.1–10.0
White—DOCS	0–60	6.7	1897	6.2–7.2
White—certified observers	0–60	8.2	224	6.6–9.8
White—DOCS	0–40	5.9	1686	5.4–6.3
White—certified observers	0–40	7.4	199	5.7–9.0

[1]99% CI = 99% confidence interval

Over the full range of opacity (*i.e.*, 0 to 100%), the mean opacity difference (*i.e*., DOCS opacity reading minus the transmissometer opacity reading) for black smoke was estimated to be 6.4 % with a 99 % confidence interval that ranged from 6.0 to 6.8. These results demonstrate that, for black smoke, the DOCS has a margin of error in measuring plume opacity that is significantly less than the acceptable margin of error associated with Method 9 (*i.e.*, 7.5%) [8]. These statistical results, which specifically address the primary technology performance criteria, support the conclusion that the accuracy of the DOCS to quantify the visible opacity of black smoke is equal to or greater than what is required to certify under Method 9.

Similarly, the field data indicated that, when the opacity of white smoke was held below 60%, the DOCS technology consistently achieved the Method 9 accuracy standard. As for black smoke, these results demonstrate that the DOCS technology field test results fully meet the primary performance criteria. In contrast, within the same opacity range, Method-9-certified visual observers reported opacity measurements that yielded mean differences that were significantly greater than the acceptable margin of error associated with Method 9 [8].
With the overwhelming success of the DOCS performance at the Ogden, Utah, smoke school, the Opacity Science Advisory Panel in conjunction with the EPA's Emission Measurement Center requested that a manuscript summarizing the findings from the field demonstration be prepared and submitted to a peer-reviewed technical journal. The Hill AFB environmental management directorate accepted the task of drafting the technical manuscript, which was published by the *Journal of the Air & Waste Management Association* (*JAWMA*) in 2003 [6].

4.3.2 Phase I—Augusta, Georgia, Smoke School

The climatic conditions recorded during the Augusta, Georgia, smoke school were characterized by scattered clouds and partly overcast skies (Table 4-4). Not only were the weather conditions in Augusta, Georgia, found to be appreciably different from those encountered in Ogden, Utah, but the physical landscape of the two smoke school locations were drastically different as well. For example, while the Ogden, Utah, smoke school field tests were conducted in a large open parking lot located adjacent to a university athletic stadium, the venue for the Georgia smoke school was a smaller and more secluded parking lot surrounded by a dense pine forest. The combination of cloudy conditions and tall trees provided a more variable background against which the DOCS and Method 9-certified human observers were estimating plume opacity.

Table 4-4 Climatic Conditions During DOCS Smoke Field Demonstration in Augusta, Georgia

Parameter	Day of Test		
	Day 1	Day 2	Day 3
Mean Temperature (° F)	63.1	60.0	67.5
Average Wind Speed (mph)	4.0	5.3	5.0
Maximum Wind Speed (mph)	4.6	11.5	9.2
Wind Direction	N	N	S–SE
Sky Conditions	Partly Cloudy	Scattered Clouds	Cloudy
Relative Humidity (percent)	50.9	72.0	90.9
Visibility (miles)	10.0	10.0	7.9
Barometric Pressure (in. of Hg)	30.36	30.42	30.27
Precipitation (in.)	0	0	0
Vertical Sun Angle (degrees)	32.4	31.0	28.6

4.3.2.1 *Quantitative Analysis—Augusta, Georgia, Smoke School*

Table 4-5 provides a summary of the DOCS technology statistical data generated from the Augusta, Georgia, smoke school field demonstration tests. Over the full range of opacity for black smoke, neither the DOCS technology nor the Method-9-certified human opacity readers were able to meet the accuracy requirements established by EPA Reference Method 9. The mean opacity difference recorded by the DOCS technology for black smoke was 8.6% while Method-9-certified readers recorded a mean difference of 8.4%. Despite the inability of the DOCS technology to achieve the accuracy standard specified for supporting method equivalency during the Augusta, Georgia, field tests, the variability in the DOCS analyses (as reflected in the range of the statistical confidence intervals) was significantly *less* than that found for Method-9-certified smoke readers [6]. This observation supports one of the primary field demonstration performance criteria, namely that the DOCS technology is inherently more reliable than Method 9.

Table 4-5 Statistical Data Summary of Augusta, Georgia, Smoke School DOCS Evaluation

Color of Smoke— Opacity Measurement Approac	Opacity Range (%)	Mean Deviation (%)	Number of Samples	99% CI[1]
Black—DOCS	0 – 100	8.6	4949	8.3 – 9.0
Black—certified observers	0 – 100	8.4	543	5.5 – 11.3
Black—DOCS	0 – 60	8.2	3620	7.8 – 8.6
Black—certified observers	0 – 60	6.1	398	5.2 – 7.1
Black—DOCS	0 – 40	7.9	2896	7.4 – 8.3
Black—certified observers	0 – 40	4.7	315	3.8 – 5.6
White—DOCS	0 – 100	13.2	3535	12.5 – 13.9
White—certified observers	0 – 100	6.2	365	5.2 – 7.2
White—DOCS	0 – 60	8.5	2565	8.0 – 9.1
White—certified observers	0 – 60	4.9	265	4.0 – 5.8
White—DOCS	0 – 40	7.2	2203	6.6 – 7.7
White—certified observers	0 – 40	4.1	227	3.4 – 4.9

[1]99% CI – 99% confidence interval

Over the limited opacity range of 0 to 60% for black smoke, Method-9-certified readers appear to be more accurate than the DOCS with a reported mean difference of 6.1% compared to 8.2% estimated for the DOCS. The reasons for the improved accuracy of Method-9-certified smoke readers to quantify opacity under the smoke school environment was most likely due to the fact that, with the relatively small stack height associated with the EPA smoke generator (*ca*. 15 feet), human observers could easily utilize a background other than sky (*e.g.*, vegetation, telephone poles, bill boards, etc.) to improve the level of contrast exhibited by the plume, while the DOCS

was limited to the use of sky. Although utilization of background other than sky is permissible during Method 9 smoke certification testing, during the regulatory application of Method 9, human observers often have to estimate the opacity of plumes generated from stacks that are positioned on top of buildings or are otherwise located above the local tree lines. Under these conditions, the visual observer is compelled to utilize sky as background.

4.3.3 Phase I—Columbus, Ohio, Smoke School

The climatic conditions recorded during the Columbus, Ohio, smoke school are summarized in Table 4-6. With respect to evaluating opacity, the weather conditions during the Columbus, Ohio, field tests were considerably poorer when compared to either the Utah or Georgia smoke schools. The weather conditions in Columbus, Ohio, for the DOCS technology field tests were characterized by freezing temperatures, light rain mixed with snow, and thick, overcast skies.

Table 4-6 Climatic Conditions During DOCS Smoke Field Demonstration in Columbus, Ohio

Parameter	Day of Test		
	Day 1	Day 2	Day 3
Mean Temperature (° F)	32.0	33.0	37.0
Average Wind Speed (mph)	7.8	6.9	5.1
Maximum Wind Speed (mph)	13.8	11.5	13.8
Wind Direction	NW	NW	S
Sky Conditions	Freezing Rain, Overcast	Haze, Overcast	Overcast, Scattered Clouds
Relative Humidity (percent)	93.0	83.2	95.0
Visibility (miles)	5.5	8.5	5.7
Barometric Pressure (in. of Hg)	29.98	30.18	30.15
Precipitation (in.)	0.77	0	0
Vertical Sun Angle (degrees)	no sun	38.0	46.0

4.3.3.1 *Quantitative Analysis—Columbus, Ohio, Smoke School*

A summary of the DOCS technology statistical data obtained from the Columbus, Ohio, smoke school is presented in Table 4-7. Over the full range of opacity for both black and white smoke, neither the DOCS technology nor the Method-9-certified human opacity readers were able to achieve the accuracy standard defined by Method 9. The failure of both the DOCS and Method-9-certified smoke readers to achieve the Method 9 accuracy levels was unexpected but not surprising given the challenging weather conditions. A common concern expressed by many of the smoke school participants was their inability to actually visualize the plume using the sky as background.

Table 4-7 Statistical Data Summary of the Columbus, Ohio, Smoke School DOCS Evaluation

Color of Smoke— Opacity Measurement Approach	Opacity Range (%)	Mean Deviation (%)	Number of Samples	99% CI[1]
Black—DOCS	0 – 100	10.9	3498	10.4 – 11.5
Black—certified observers	0 – 100	12.0	1492	11.3 – 12.7
Black—DOCS	0 – 60	9.4	3066	8.9 – 9.8
Black—certified observers	0 – 60	10.6	1192	9.9 – 11.3
Black—DOCS	0 – 40	8.1	2753	7.6 – 8.5
Black—certified observers	0 – 40	9.2	1012	8.5 – 9.9
White—DOCS	0 – 100	21.6	4394	20.8 – 22.4
White—certified observers	0 – 100	10.0	1500	9.4 – 10.6
White—DOCS	0 – 60	15.0	3758	14.4 – 15.5
White—certified observers	0 – 60	9.7	1176	9.1 – 10.4
White—DOCS	0 – 40	12.3	3131	11.9 – 12.7
White—certified observers	0 – 40	9.5	1020	8.8 – 10.3

[1]99% CI = 99% confidence interval

4.3.4 Significance Testing

The initial documentation of method equivalency was established through computing the confidence intervals about the mean difference between the DOCS technology and EPA-certified transmissometer opacity readings. Based on a recommendation received from the EPA's Emission Measurement Center, statistical significance testing was conducted as well.

In significance testing, a null hypothesis (H_o) is developed that will be assumed to be true in the absence of strong quantitative evidence to the contrary [10, 11]. The null hypothesis (H_o) for the present study may be stated as follows: "The true mean difference between the transmissometer and the DOCS opacity measurement methods is greater than 7.5%". This statement reflects the assumption that, in the absence of strong quantitative data to the contrary, the two opacity measurement methods are not equivalent. Similarly, the alternative hypothesis (H_a) may be constructed as follows: "The true mean difference between the transmissometer and the DOCS opacity measurement method is equal to or less than 7.5%". The rationale for constructing the null and alternative hypothesis in this fashion is to shift the burden of proof for demonstrating Method 9 equivalency to the strength of the DOCS field demonstration data (Equation 1).

Null Hypothesis (H_0): $\delta_0 > 7.5\%$

Alternative Hypothesis (Ha): $\delta_0 \leq 7.5\%$ (1)

Where δ_0 = true mean difference (opacity measured using DOCS – opacity measured using a transmissometer)

In other words, in the absence of field data that strongly support the rejection of the null hypothesis, the conclusion drawn from the data will be that DOCS technology is not equivalent to Method 9. Alternatively, if the strength of the data is sufficient to reject the null hypothesis (acceptance of H_a), the conclusion drawn from the data will be that the DOCS technology is statistically equivalent to Method 9.

Given an assigned level of significance, α, and degrees of freedom (n-1), Equations 2 and 3 define the critical t-value and test-statistic (t_{test}), respectively. These parameters are compared to determine whether the strength of the data is sufficient to reject the null hypothesis as depicted by the statistical test condition.

$$\text{Critical } t \text{ - value} : t_{\frac{\alpha}{2}, n\text{-}1} \qquad (2)$$

$$\text{Test statistic} : t_{\text{test}} = \frac{\bar{d} - \delta_o}{\frac{s_d}{\sqrt{n}}} \qquad (3)$$

Where

n: Number of paired measurements (*i.e.*, DOCS–transmissometer)

$\bar{d}$: Mean difference between DOCS and transmissometer measurements

$\frac{s_d}{\sqrt{n}}$: Standard error

s_d: Square root of variance

Equation 4 illustrates the statistical test conditions used to support or reject the null hypothesis. In practical terms, rejection of the null hypothesis is tantamount to accepting the DOCS technology as an equivalent method to Method 9, whereas failure to reject the null hypothesis essentially means that the DOCS technology is not a statistically equivalent method. Table 4-8 summarizes the results of hypothesis testing using data obtained from the three EPA-approved smoke schools.

<u>STATISTICAL TEST CONDITIONS</u>

Test Condition: If $t_{\text{test}} < t_{\frac{\alpha}{2}, n\text{-}1}$, then the null hypothesis, H_0, is rejected

Test Condition: If $t_{\text{test}} > t_{\frac{\alpha}{2}, \text{n-1}}$, data do not support rejection of the null hypothesis, H_0, (accept H_a). (4)

Table 4-8 Summary of Hypothesis Testing Performed at the 0.05 Significance Level

Smoke School	Color of Smoke	Opacity Range (%)	Mean Difference (%)	Number of Samples	Significance Level (α)	Critical[1] *t*-value	Test Statistic	Reject[2] Null Hypothesis?
Utah								
	Black	0–100	6.4	2236	0.05	1.96	-6.77	Yes
	Black	0–60	5.6	1957	0.05	1.96	-12.08	Yes
	Black	0–40	5.4	1745	0.05	1.96	-12.50	Yes
	White	0–100	10.0	2405	0.05	1.96	10.39	No
	White	0–60	6.7	1897	0.05	1.96	-4.35	Yes
	White	0–40	5.9	1686	0.05	1.96	-8.99	Yes
Georgia								
	Black	0–100	8.6	4949	0.05	1.96	8.06	No
	Black	0–60	8.2	3620	0.05	1.96	4.49	No
	Black	0–40	7.9	2896	0.05	1.96	2.22	No
	White	0–100	13.2	3535	0.05	1.96	19.93	No
	White	0–60	8.5	2565	0.05	1.96	4.72	No
	White	0–40	7.2	2203	0.05	1.96	-1.47	Yes
Ohio								
	Black	0–100	10.9	3498	0.05	1.96	16.83	No
	Black	0–60	9.4	3066	0.05	1.96	10.24	No
	Black	0–40	8.1	2753	0.05	1.96	3.53	No
	White	0–100	21.6	4394	0.05	1.96	46.81	No
	White	0–60	15.0	3758	0.05	1.96	36.32	No
	White	0–40	12.3	3131	0.05	1.96	28.67	No

[1]From standard statistical tables, for $\alpha = 0.05$ and $n > 120$, *t*-critical is approximately 1.96

[2]Where the null hypothesis is rejected, the data indicate that DOCS is *equivalent* to EPA Reference Method 9. Conversely, if the null hypothesis is not rejected, the conclusion is that DOCS is *not equivalent* to EPA Reference Method 9.

Significance testing yielded mixed results with respect to the equivalency of the DOCS technology to Method 9. In all but one opacity range (high white plumes), the data from the Utah smoke school supported rejection of the null hypothesis indicating that the conclusion drawn from the data should be that the DOCS technology is equivalent to Method 9. Conversely, in the Georgia and Ohio smoke schools, the DOCS technology field data, in general, failed to support the rejection of the null hypothesis. Only in the limited opacity range of 0 to 40% for white smoke plumes in the Augusta, Georgia, field tests did the data suggest that the DOCS technology was statistically equivalent to Method 9. The results for the three smoke

school field tests seem to indicate that climatic conditions have a profound effect on the ability of the DOCS technology to accurately measure plume opacity. During the Utah field test, sky conditions were clear, which provided optimal visual contrast between the smoke plume and sky. Under clear blue skies, the accuracy of the DOCS in measuring plume
opacity was significantly better than the established Method 9 accuracy standard. Alternatively, when smoke plumes were viewed under weather conditions characterized by cloudy or overcast skies, the DOCS technology has difficulty in accurately quantifying opacity. However, under these same conditions, the accuracy of Method 9-certified human observers in estimating visible opacity was also severely diminished [6].

At the conclusion of Phase I of the DOCS technology field demonstration, both the EPA's Emission Measurement Center and the Optical Science Advisory Panel strongly encouraged the development and submission of a technical manuscript summarizing all the smoke school data to a peer-reviewed scientific journal. Hill AFB environmental management directorate accepted the task of preparing and submitting the technical manuscript, which was published by the *Journal of the Air & Waste Management Association* (*JAWMA*) in 2004 [12].

4.3.5 Phase II—DOCS Technology Field Demonstration

Mild temperatures, overcast skies and precipitation characterized the climate during the DOCS technology Phase II field demonstration activities. On-site field personnel recorded the values of specific climatic parameters including 1) mean air temperature, 2) average wind speed, 3) maximum wind speed, 4) sky conditions, 5) relative humidity, 6) visibility, 7) barometric pressure, 8) precipitation, 9) horizontal sun angle and 10) vertical sun angle. Table 4-9 provides a summary of

Table 4-9 Climatic Conditions for DOCS Phase II Field Demonstration in Alaska

Parameter	Day of Test	
	Day 1	Day 2
Mean Temperature (° F)	54.0	41.9
Average Wind Speed (mph)	4.5	1.2
Maximum Wind Speed (mph)	10.4	4.6
Wind Direction	Not measured	Not Measured
Sky Conditions	Rain, Overcast	Mist, Overcast
Relative Humidity (percent)	100	96
Visibility (miles)	6.0	3.0
Barometric Pressure (in. of Hg)	29.56	29.74
Precipitation (in.)	0.82	0.00
Vertical Sun Angle (degrees)	No sun visible	No sun visible

weather conditions that occurred during the two days of the DOCS field testing in the cities of Anchorage and Healy, Alaska, is provided in. It should be noted that the dark overcast skies made it virtually impossible to visually detect and measure a vertical sun angle at both the Anchorage and Healy DOCS technology field demonstration sites.

4.3.5.1 *Quantitative Analysis—DoD Industrial and Commercial Sites*

In Phase II, the DOCS technology was employed to quantify the visual opacity associated with DoD industrial and commercial processes in the state of Alaska. Except for the EPA-certified smoke generator in Anchorage and the coal-fired power plant in Healy, none of the regulated air sources were equipped with opacity monitors. In the absence of a COM, the opacity data collected from these air sources were used to determine whether the DOCS technology and Method-9-certified opacity readers yielded opacity measurement results that were statistically different. Table 4-10 summarizes the DOCS technology field demonstration data from those air sources equipped with a COMs.

Table 4-10 DOCS Opacity Measurements of Sources Equipped with a Continuous Opacity Monitor (COM)

Opacity Measurement Approach	Opacity Range (%)	Mean Difference (%)	Number of Samples	99% CI[1]
DOCS—COM	0–100%	14.1	215	11.6–16.6
Certified observers—COM	0–100%	6.0	224	5.2–6.8

[1]99% CI = 99% confidence interval

Table 4-11 summarizes the statistical comparison between the mean DOCS opacity measurement and the mean opacity measurement recorded by Method-9-certified human observers at regulated air sources where there was no COM installed. When the comparison was made using a limited opacity range of 0 to 40% (based on Method-9-certified reader measurements), the mean opacity difference between the DOCS technology and certified human observers decreased to 5.0 %. These data suggest that the difference between the two methods in measuring visible opacity is significant and that, on average, the DOCS tends to read visible emissions at higher opacity levels than Method-9-certified human observers [13].

Table 4-11 Statistical Data Summary of Alaska Field Measurements without COM

Opacity Measurement Approach	Opacity Range (%)	Mean Difference (%)	Number of Samples	99% CI[1]
DOCS—Certified observers	0–100	10.5	360	8.9–12.2
DOCS—Certified observers	0–40	5.0	255	3.7–6.3

[1]99% CI = 99% confidence interval

With respect to achieving the technology accuracy performance criteria, Phase I and II field demonstration results confirmed that the DOCS technology consistently achieved the federally codified Method 9 accuracy standard when the technology was employed under clear (*i.e.*, blue sky) weather conditions. Moreover, using the width of the 99% confidence about the mean

opacity difference as a metric for reliability, the field demonstration results confirmed that the reliability of the DOCS technology exceeded that of Method 9 for all types of smoke plumes and under all weather conditions. The superior reliability of the DOCS technology was not surprising given the fact that estimation of visible opacity using a digital camera based system is much less subjective than employing human observers.

Although the DOCS technology was inconsistent in achieving the codified Method 9 accuracy standard when evaluated under adverse weather conditions, the regulatory approved opacity measurement approach (*i.e.*, Method 9-certified human observers) consistently failed to maintain the accuracy standard when evaluated under these same climatic conditions. These findings suggest important technical limitations and considerations for DoD personnel tasked with measuring and reporting visual opacity. First, the DOCS technology would be the preferred approach over Method-9-certified readers when measuring visible opacity under fair weather (*e.g.*, clear sky) conditions. Secondly, under adverse weather conditions, the diminished measurement accuracy experienced by the DOCS technology is comparable to the reduced measurement accuracy documented by Method-9-certified human observers. Despite its reduced accuracy under poor weather conditions, its superior reliability suggests that the DOCS technology would be the superior opacity measurement method under all weather conditions. Third, the poor performance of the Method-9-certified human observers in estimating visible opacity under overcast sky conditions clearly illustrates not only that the current federally approved opacity measurement approach is subjective but that success in completing Method 9 certification training provides little assurance that the Method 9-certified human observer can estimate the opacity of regulated air sources with any known degree of confidence.

Finally, owing to both the scientific and regulatory significance of the Phase II DOCS field demonstration activities, the EPA's Emission Measurement Center in conjunction with the Opacity Science Advisory Panel strongly recommended that the key findings of the DOCS Phase II demonstration activities be summarized and published in a peer-reviewed journal article. Hill AFB environmental management directorate accepted the responsibility of preparing and submitting a technical manuscript of the DOCS Phase II field demonstration, which was published by the *Federal Facilities Environmental Journal* in 2004 [13].

5. Cost Assessment

5.1 Cost Reporting

Tables 5-1 and 5-2 summarize the estimated costs associated with the implementation of Method 9 at a DoD stateside and remote location, respectively. Although, in principle, there are no specifically required Method 9 equipment costs, in practice, the Method 9 visual opacity reader must purchase or at least have access to a range of climatic monitoring equipment including the following 1) anemometer, 2) sling psychrometer, 3) Abney Level (sun angle measurement), 4) stop watch and 5) magnetic compass. The total purchase price for these instruments is approximately $2,000.00, which does not include an annual equipment maintenance costs estimated at $200.00.

Table 5-1 Method 9 Implementation Costs at a Stateside DoD Facility

Direct Environmental Activity Process Cost				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation and Maintenance**					
Activity	$ K	Activity	$ K	Activity	$ K	Activity	$ K
Method 9 Equipment purchase	0	Consumables and Supplies	0.025	Compliance Audits	0	Overhead Associated With Process	0
Equipment Design	NA	Equipment Maintenance	0	Document Maintenance	0.06	Productivity/ Cycle Time	2.4
Training operators	4.1	Training of Operators	8.2	Environmental Management Plan Maintenance	0.06	Worker Injury Claims & Health Costs	0
Environmental Monitoring Equipment	2.0	Environmental Monitoring Equipment	0.2	Reporting Requirements	0.12		
SUMMARY OF COSTS							
Total Initial Investment Costs[1]	**6.1**	**Total Direct Operation and Maintenance Costs**	**8.425**	**Total Indirect Environmental Activity Costs**	**0.24**	**Total – Other Costs**	**2.4**
Total Annual Operating Costs[2] (8.425 + 0.24 + 0.24)	**8.905**						

[1]Total Initial Investment Costs consist of only Start-Up Costs
[2]Total Annual Operating Costs consist of Total Direct O&M, Total Indirect Environmental Activity Costs and Other Costs

Method 9 certification training costs were estimated to be approximately $4,100.00 per stateside facility trainee and $6,300.00 per trainee located at a remote DoD facility. The relatively large difference in training costs between stateside and remote DoD locations is directly attributable to the need to hire temporary contract labor at remote facilities to cover assigned worker duties when full time employees are attending Method 9 training.

The Method 9 training requires that the trainees undergo a three-(3)-day training program that basically consists of one day of classroom instruction followed by two days of opacity field testing. For the stateside facilities, the Method 9 training costs for a minimum of two (2) individuals consists of the following items: 1) $350.00 tuition per attendee, 2) labor costs at $15.00/hr for 40 hours and 3) $1100.00 travel costs per attendee. For DoD personnel stationed at remote locations, the Method 9 training cost for a minimum of two (2) individuals consists of: 1) $350.00 tuition per attendee, 2) labor costs at $15.00/hr for 40 hours, 3) replacement labor costs at $15.00/hr for 40 hours, 4) $1100.00 travel costs per attendee and 5) $1100.00 travel costs

Table 5-2 Method 9 Implementation Costs at a Remote DoD Facility

Direct Environmental Activity Process Cost				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation and Maintenance**					
Activity	$ K	Activity	$ K	Activity	$ K	Activity	$ K
Method 9 Equipment purchase	0	Consumables and Supplies	0.025	Compliance Audits	0	Overhead Associated with Process	0
Equipment Design	NA	Equipment Maintenance	0	Document Maintenance	0.06	Productivity/ Cycle Time	4.8
Training Operators	6.3	Training of Operators	12.6	Environmental Management Plan Maintenance	0.06	Worker Injury Claims & Health Costs	0
Environmental Monitoring Equipment	2.0	Environmental Monitoring Equipment	0.2	Reporting Requirements	0.12		
SUMMARY OF COSTS							
Total Initial Investment Costs[1]	**8.3**	**Total Direct O&M Costs**	**12.83**	**Total Indirect Environmental Activity Costs**	**0.24**	**Total – Other Costs**	**4.8**
Total Annual Operating Costs[2] (12.825 + 0.24 + 0.48)	**13.55**						

[1]Total Initial Investment Costs consist of only Start-Up Costs
[2]Total Annual Operating Costs consist of Total Direct O&M, Total Indirect Environmental Activity Costs and Other Costs

per replacement labor. Indirect costs, which include environmental document storage and maintenance, are estimated to be approximately $240.00 per year.

Productivity/cycle time costs are associated with worker productivity losses directly attributable to a worker receiving salary but essentially being absent from official duties during Method 9 training. At stateside facilities, the financial value of worker productivity loss associated with Method 9 is anticipated to be $2,400.00. This estimate consists of the costs associated with individuals being absent from their full-time work assignment for 40 hours at a pay rate of $15.00/hr twice per year. Similarly, for DoD personnel stationed at remote sites, productivity/cycle time costs are estimated to be approximately $4,800.00. This estimate includes the costs associated with full-time employees (2) and temporary hires (2) being absent from their full-time work assignment for 40 hours at a pay rate of $15.00/hr twice per year. Consumables and supplies in support of Method 9 measurements are estimated to be $25.00 per year.

Table 5-3 DOCS Implementation Costs at a Stateside DoD Facility

Direct Environmental Activity Process Cost				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation and Maintenance**					
Activity	$ K	Activity	$ K	Activity	$ K	Activity	$ K
DOCS Equipment purchase	3.00	Consumables and Supplies	0.075	Compliance Audits	0	Overhead Associated with Process	0
Equipment Design	NA	Equipment Maintenance	0.10	Document Maintenance	0.06	Productivity/ Cycle Time	0.48
Training Operators	3.14	Training of Operators	0.50	Environmental Management Plan Maintenance	0.06	Worker Injury Claims & Health Costs	0
Environmental Monitoring Equipment	2.00	Environmental Monitoring Equipment	0.20	Reporting Requirements	0.12		
SUMMARY OF COSTS							
Total Initial Investment Costs[1]	**8.14**	**Total Direct O&M Costs**	**0.88**	**Total Indirect Environmental Activity Costs**	**0.24**	**Total – Other Costs**	**4.8**
Total Annual Operating Costs[2] (0.875 + 0.24 + 0.48)	**5.92**						

[1]Total Initial Investment Costs consist of only Start-Up Costs
[2]Total Annual Operating Costs consist of Total Direct O&M, Total Indirect Environmental Activity Costs and Other Costs

Tables 5-3 and 5-4 summarize the estimated implementation costs for supporting a DOCS opacity measurement program for a single regulated source at a state-side and remote DoD location, respectively. The capital costs for the DOCS technology is approximately $3,000.00 and includes the purchase of a medium-end digital camera with five-year service contract (@ $750.00), laptop computer with five-year service contract (@ $1,500.00), DOCS software license (@ 500.00) and instructional CD together with other accessories (@ $250.00). Although, in theory, these costs represent one-time sunk costs, in reality, digital camera and computer software technology continue to evolve and improve. For the DOCS technology to take full advantage of future scientific advancements, it is anticipated that DOCS software version releases compatible with improved digital camera hardware will be developed and made available to purchasers of DOCS software licenses.

Table 5-4 DOCS Implementation Costs at a Remote DoD Facility

Direct Environmental Activity Process Cost				**Indirect Environmental Activity Costs (Annual)**		**Other Costs (Annual)**	
Start-Up		**Operation and Maintenance**					
Activity	$ K	Activity	$ K	Activity	$ K	Activity	$ K
Equipment purchase	3.00	Consumables and Supplies	0.075	Compliance Audits	0	Overhead Associated with Process	0
Equipment Design	NA	Equipment Maintenance	0.10	Document Maintenance	0.06	Productivity /Cycle Time	0.48
Training Operators	6.06	Training of Operators	0.50	Environmental Management Plan Preparation and Maintenance	0.06	Worker Injury Claims & Health Costs	0
Environmental Monitoring Equipment	2.00	Environmental Monitoring Equipment	0.20	Reporting Requirements	0.12		
SUMMARY OF COSTS							
Total Initial Investment Costs[1]	**11.06**	**Total Direct O&M Costs**	**0.88**	**Total Indirect Environmental Activity Costs**	**0.24**	**Total – Other Costs**	**4.8**
Total Annual Operating Costs[2] (0.875 + 0.24 + 0.48)	**5.92**						

[1]Total Initial Investment Costs consist of only Start-Up Costs
[2]Total Annual Operating Costs consist of Total Direct O&M, Total Indirect Environmental Activity Costs and Other Costs

In addition to the DOCS capital costs, the DOCS user must purchase or at least have access to a range of climatic monitoring equipment including the following: 1) anemometer, 2) sling psychrometer, 3) Abney Level (sun angle measurement), 4) stop watch and 5) magnetic compass. These instruments are required for monitoring and documenting weather conditions, which are legally reportable information associated with current Method 9 opacity compliance verification activities. It is assumed that air quality regulators will continue to require opacity reporting to be accompanied by relevant climatic data regardless of the opacity measurement approach. The purchase price for these instruments is approximately $2,000.00 and annual equipment maintenance costs are estimated to be approximately $200.00. Consumables and supplies in support of the DOCS technology hardware are estimated to be approximately $75.00 per year and include such items as batteries and digital camera memory chips.

The costs associated with implementation of DOCS at state-side and remote DoD locations are essentially equivalent except for a substantial difference attributable to the hiring of temporary workers for the smaller and remotely located facilities. When travel and per diem costs are taken into account, the estimated initial DOCS training costs for a stateside DoD facility are estimated to be approximately $3,140.00. The costs elements comprising this estimate consists of the following: 1) trainee tuition at $350.00, 2) labor cost at $15/hr for eight (8) hours, 3) travel costs at $1100.00 (hotel at $300.00, per diem at $105.00, $700.00 average airline fare) and 4) two individuals being trained. It is assumed that at stateside DoD facilities, a sufficient labor force exists to cover the duties of those individuals who are absent to attend DOCS training. For a remotely located facility, the addition of hiring replacement workers increases the overall training cost to approximately $6,060. This estimate reflects the following cost elements: 1) trainee tuition at $350.00, 2) labor cost at $15/hr for eight (8) hours, 3) travel cost at $1100.00 for both attendee and replacement workers, 4) replacement labor costs (3 days or 24 hours at $15.00/hr) and 5) two individuals receiving DOCS training.

It is anticipated that DOCS training will take no more than eight (8) hours, of which the first half of the training session will focus on classroom presentations of the scientific theory upon which DOCS is based as well as a review of the fundamental operation of digital cameras and photographic principles. The second half of training will be dedicated to utilizing the DOCS software to estimate the opacity of a series of digital photographs of air sources of known opacity possibly followed by a short computer based examination.

Once the initial DOCS technology training is completed, re-certification training can be conducted for both DoD state-side and remotely located personnel through either a web-based or compact disc (CD) training program. The anticipated cost for this training is estimated to be approximately $500.00 per facility. It is also assumed that the DOCS operation and maintenance training costs includes uninterrupted access to a DOCS help desk. The DOCS help desk, which presumably will be operated by a private contractor, will provide the user with technical assistance as well as appropriate version updates to the DOCS computer software. The annual equipment operations and maintenance costs are estimated to be approximately $100.00, which includes the costs for any minor repairs associated with either the digital camera and/or the laptop computer (note that it is assumed that any major hardware repairs would be covered by service contracts included in the item's original purchase price). Indirect costs, which include environmental document storage and maintenance, is estimated to be approximately $240.00 per year. At both large and remote facilities, worker productivity loss associated with DOCS web-based or CD training is estimated at $480.00, which consists of two individuals being trained for eight (8) hours at a pay rate of $15.00/hr twice per year.

5.2 Cost Analysis

To provide a consistent basis upon which to compare life-cycle technology implementation costs, the data provided in Tables 5-1 through 5-4 are utilized to estimate the total annual costs associated with using either DOCS or Method 9 (Table 5-5). The timeframe over which the costs will be compared is five (5) years, which is considered a reasonable useful life for digital cameras and laptop computers. The assumed interest (or discount) rate used in developing the annual financial estimates is 4.0% [14].

To convert the one-time start-up activity costs to an annual (*i.e.*, amortized) cost, an equal-payment capital recovery factor (CRF) is utilized. The value of the CFR at 4.0% for a five-year period is approximately 0.2246 [14]. To estimate the total annual costs for implementation of either method, other annual cost elements are added to the amortized start-up costs. For example, the start-up costs for implementation of the DOCS at stateside DoD facilities (Table 5-3) is estimated to be $8,140.00 ($3,000.00 for DOCS hardware, $3,140.00 for initial operator training and $2,000.00 for environmental measurement equipment). Amortization of these costs yields an annual cost of $1,828.24 ($8,140.00 • 0.2246). When the other annual cost elements are added to the amortized start-up cost, the total annual cost for implementing and maintaining a DOCS system at a state-side facility is estimated to be $3,423.24.

Results from Table 5-5 illustrate that DOCS implementation results in substantial cost savings compared to Method 9 at both stateside and remote locations. The magnitude of the potential financial benefits associated with employing DOCS will vary with DoD facility size and the number of opacity inspectors currently employed at the facility. For example, the *annual* cost savings associated with implementation of DOCS on stateside facilities is approximately $9,011.82 ($12,435.06– $3,423.24) *per pair* of trained technology users. Given that DoD currently supports Method 9 certification for approximately 3,400 opacity readers (*i.e.*, 1,700 pairs of opacity readers), the aggregate annual savings to DoD in adopting DOCS would be approximately *15.3 million dollars per year*. Accounting of the annual cost savings associated with the implementation of DOCS on remote DoD facilities would yield even larger annual cost savings.

Table 5-5 Total Annual Cost Estimates for Implementing DOCS and Method 9

IMPLEMENTATION SCENARIO	Amortized Start-Up Costs[1]	Annual O&M Costs	Indirect Environmental Activity Costs	Productivity /Cycle Time Costs	**TOTAL ANNUAL COSTS[2]**
DOCS; stateside	$1,828.24	$875.00	$240.00	$480.00	**$3,423.24**
DOCS; remote location	$2,484.08	$875.00	$240.00	$480.00	**$4,079.08**
Method 9; stateside	$1,370.06	$8,425.00	$240.00	$2,400.00	**$12,435.06**
Method 9; remote location	$1,864.18	$12,825.00	$240.00	$4,800.00	**$19,729.18**

[1]Amortized costs are based on 4% discount rate applied over a five-year period—Capital Recovery Factor is approximately 0.2246
[2]Total annual costs are *per pair* of trained individuals

A net present value (NPV) analysis was employed to estimating total life-cycle costs savings. Using a discount rate of 4%, the estimated present worth factor (PWF) for a five-year product life is approximately 4.4518 [14]. Multiplying the PWF by the annual cost savings yields the NPV for each implementation scenario. The difference between the NPVs for the alternatives is essentially the life-cycle cost savings. For example, the NPV for DOCS and Method 9 stateside implementation are $15,239.58 ($3,423.24 • 4.4518) and $55,358.40 ($12,435.06 • 4.4518), respectively, *per pair* of trained technology users. The difference between these two values, $40,118.82, reflects the life-cycle cost savings per pair of trained DOCS technology users. It should be noted that if all DoD supported visual opacity readers were assumed to be stationed at stateside facilities, adoption of the DOCS technology has the potential of saving DoD in excess of *68.2 million dollars* ($40,118.82 per pair of trained DOCS technology users • 1,700 pairs of opacity readers in all of DoD) over the useful life of the DOCS equipment (estimated at five years). Table 5-6 summarizes both annual cost savings and the life-cycle cost savings associated with DoD adoption of the DOCS technology per pair of trained DOCS technology users.

Table 5-6 Annual Cost and Life-Cycle Cost Savings Associated with Implementing DOCS[1]

Annual Cost Savings to Implement DOCS at Stateside DoD Location[2]	Annual Cost Savings to Implement DOCS at Remote DoD Location[3]	Life-Cycle Cost Savings to Implement DOCS at Stateside DoD Location	Life-Cycle Cost Savings to Implement DOCS at Remote DoD Location
$9,011.82	$15,650.10	$40,118.82	$69,671.12

[1]Cost basis is *per pair* of trained technology users at a facility

[2]($12,435.06 – $3,423.24) see Table 5-5

[3]($19,729.18 – $4,079.08) see Table 5-5

Finally, the ability of the DOCS technology to archive digital photographs of visible opacity represents another potential cost savings to regulated DoD facilities. In principle, this ability improves the forensic reliability of the opacity measurement, which can potentially reduce the number of legal enforcement actions that a regulatory agency may take against a facility. With a significant number of DoD air sources required to operate within a specified opacity range, providing regulatory agencies with an opacity measurement accompanied by a digital photograph of the source during operation would be more compelling evidence of the actual opacity level and provide irrefutable evidence of the source's compliance status. Moreover, regulatory agencies could analyze the digital photograph at any time using the DOCS software (or equivalent approach) to verify the reported opacity level.

5.3 Cost Comparison

As illustrated in Tables 5-5 and 5-6, the DOCS technology represents a financially competitive alternative to either Method 9 or a continuous opacity monitor (COM) for measuring the visual opacity of regulated air sources. Method 9 compliance costs consist of budgeting resources for training individuals every six months. Given the Method 9 training and lost worker productivity costs cited in Table 5-5, and the fact that DoD currently certifies 3,400 individuals in Method 9,

the resource level required to support Method 9 across the entire DoD is estimated at approximately $21.1 million dollars per year (stateside costs at $12,435.06 per pair of trained individuals • 1,700 pairs of trained individuals). If the percentage of Method 9-certified individuals who are actually stationed at remote locations were taken into account, the full cost of supporting a Method 9 certification program would be much greater than the $21.1 million dollars per year estimate.

In contrast, the annual costs to implement and maintain the DOCS technology are approximately *76% less* than those required to implement and maintain Method 9 certification. Therefore, adoption of DOCS across the DoD has the potential of saving approximately *15.3 million dollars per year* in compliance costs. As a third option, a facility may opt to install and operate a COM at a substantially higher cost than either Method 9 or DOCS. Purchase prices for a single COM unit can vary from $25,000.00 to $100,000.00 per source. Moreover, at DoD facilities employing a COM, an alternative opacity measurement approach is typically required during those times when the COM experiences a breakdown or is otherwise inoperable.

Acceptance of the DOCS technology as an approved regulatory alternative to Method 9 is the largest and most important cost driver in all of these comparisons. The future of the DOCS technology and all other digital-camera-based opacity measurement technologies is highly sensitive to the development and promulgation of an EPA-approved digital-camera-based opacity verification test method. Beyond the financial impact stemming from regulatory approval of the DOCS, better-quality and lower-cost digital equipment is continuously being introduced into the marketplace. If the DOCS technology improvements can be supported to take advantage of new scientific and product development, user costs should continue to decrease. Finally, it should be noted that the DOCS technology contains no inherent hazardous chemicals and system disposal requires no unique methodology.

6. Implementation Issues

6.1 Cost Observations

The overarching factor that affected project demonstration costs was regulatory acceptance of the technology. Although the DOCS technology is relatively inexpensive to purchase and implement, many facilities that would have been ideal demonstration sites were reluctant to allow the DOCS team to evaluate their regulated air emission sources with an experimental device that had yet to receive regulatory approval. To identify and gain facility permission to apply the technology at regulated facilities required lengthy negotiations as well as regulatory assurances that participating facilities would not be susceptible to enforcement action based on the DOCS field demonstration results. It is anticipated that once final EPA approval of a digital-camera based opacity measurement method is established, legal concerns expressed by the regulated community regarding participation in future DOCS field demonstrations will be minimized, if not eliminated.

Beyond the cost impacts associated with the lack of regulatory approval of DOCS, poor weather conditions had an impact on demonstration costs. Under ideal conditions, opacity measurements are typically conducted under weather conditions characterized by light to no wind and little to no precipitation. In the current demonstration, the field demonstration schedule was established months before actual testing occurred. At many sites, opacity measurements were made under adverse weather conditions (*e.g.*, high wind, heavy precipitation, dark overcast skies, etc.). When possible, attempts were made to delay the collection of field data until weather conditions improved (which increased costs). In other circumstances, personnel travel schedules did not permit the delaying of the data collection activities.

6.2 Performance Observations

With respect to the primary performance criteria, results from the field demonstration illustrated that the DOCS consistently achieved the federally codified Method 9 accuracy standard when the technology was employed under blue sky weather conditions. Although the DOCS was inconsistent in achieving the primary performance criteria when evaluated under adverse weather conditions, the regulatory approved opacity approach (i.e., use of Method 9-certified human observers) consistently failed to achieve the accuracy standard when evaluated under these same climatic conditions. These findings clearly illustrate that the current federally approved opacity measurement approach (i.e., use of Method 9-certified human observers) is not only subjective but that success in completing Method 9 certification training provides little assurance that the Method 9-certified human observer can estimate the opacity of regulated air sources with any known degree of confidence.

The secondary performance criteria focused on the reliability of DOCS relative to Method 9-certified human observers. Using the width of the 99% confidence about the mean opacity difference as a metric for reliability, the field demonstration results confirmed that the DOCS performance exceeded that of Method 9 under all types of smoke plumes and weather conditions. The superior reliability of the DOCS technology was not surprising given the fact that estimation of visible opacity using a digital camera based system is much less subjective than employing human observers.

6.3 Other Significant Observations

After a comprehensive technical review of the DOCS field demonstration results and in light of continuous appeals by EPA regional offices, state regulatory agencies and the regulated community (including DoD facilities) for the establishment of a new EPA-approved visible opacity field measurement method as an alternative to Method 9, the EPA's Emission Measurement Center (EMC) recommended that the DOCS technical team formulate and conduct a one-year DOCS regulatory pilot study in which the DOCS would be evaluated side-by-side with Method-9-certified human observers under regulatory enforcement conditions. The DOCS regulatory pilot study, which is due to be completed in the spring of 2005, involved quantifying the visible opacity of regulated air sources located at Fort Hood, Texas, Hill AFB, Utah, Fort Wainwright, Alaska, as well as a range of regulated air sources associated with government and private industrial entities currently operating within the state of Utah.

The field results from the DOCS one-year regulatory pilot study will not only provide additional DOCS field performance data collected under regulatory enforcement conditions but will also serve as the technical basis upon which a new EPA-approved digital-camera-based visible opacity measurement method will be developed. It is anticipated that a draft digital-camera-based opacity method will be available for EPA review and consideration at the conclusion of the DOCS regulatory pilot study.

Finally, the potential application of DOCS for monitoring and enforcing opacity standards associated with fugitive emissions has not escaped the notice of federal and state regulatory agencies as well as many DoD facilities. Because of its successful deployment in the measurement of opacity associated with stationary sources, the EPA's Emission Measurement Center (EMC) has encouraged its DoD partners to consider developing and implementing a DOCS field demonstration program in which the technology may be applied to support DoD environmental compliance requirements associated with DoD operational and test range activities as well as the military operation of marine vessels.

6.4 Lessons Learned

For the potential user of the DOCS technology, there were several important lessons learned that will impact technology implementation. The first is that it must be recognized that digital camera technology is changing rapidly. The two medium-priced digital cameras that were employed in the DOCS field demonstration—Kodak DC265 and Kodak DC290—are no longer commercially available. Similar-priced digital cameras today have much improved optical qualities including enhanced picture resolution as well as long-range zoom and faster data transfer capabilities. To ensure that future DOCS users will have access to affordable digital cameras that have been validated for use with the DOCS software, the DOCS one-year regulatory pilot study has included a series of field tests in which the following commercially available digital cameras will be evaluated for measuring visible opacity: 1) Sony Cybershot DSC-WI, 2) Fuji Finepix E500, 3) Nikon Coolpix 5200 and 4) Kodak Model 6490.

Another important lesson learned is that weather conditions must be considered prior to use of the DOCS as well as Method 9. Although Method 9 does not specify weather conditions under which visible opacity should *not* be estimated, the current field demonstration results confirmed that the performance of both methods diminishes when applied during adverse weather conditions.

Finally, a recurring statement made to the DOCS field demonstration team by both DoD and regulatory agency personnel was that no alternative opacity measurement technology would be considered if it required more technical effort and/or financial resources to deploy than Method 9. Once they had an opportunity to use the technology, participating DoD and regulatory agency personnel found that the DOCS' ability to archive digital photographs of visible opacity as well as its ease of use in estimating opacity were highly favorable characteristics. The positive feedback received from DoD facilities and state regulatory agencies illustrated that there exists a sizable market for the technology once regulatory approval is obtained.

6.5 End-User Issues

The road ahead for digitally imaging and quantifying plume and/or dust opacity has been given positive initial definition by the DOCS. However, important technology maintenance and regulatory issues remain. These are summarized in the following bullets:

- New, open-source algorithms must be developed. Air Force-funded efforts are underway to scope these possibilities and determine what options are most promising. Funding to assure complete development and technical capability remains an unknown.
- Long-term support for a DOCS based system [*i.e.*, help desk functions, continued technical development support, etc.] would have to be agreed to and supported by the EPA in conjunction with other government partners. EPA will list as a conditional method the performance-based requirements of the DOCS.
- The EPA will pursue permit-based options for the use of DOCS. In a permit agreement the DOCS can be used as a technique for assuring that the air pollution control system is being operated properly to minimize visible emissions.

6. 6 Approach to Regulatory Compliance and Acceptance

Since the ultimate goal of the current field demonstration was to receive regulatory approval for the use of the DOCS by regulated DoD facilities, the US Environmental Protection Agency (EPA) as well as several state regulatory agencies were involved in all aspects of the DOCS field demonstration study.

The US EPA's Emissions Measurement Center (EMC) was an active participant in the field demonstration program and was integral in assessing both the scientific underpinnings of the DOCS technology as well as the regulatory hurdles associated with the eventual application of a digital-camera-based opacity technology by the regulated community. The DOCS field data demonstration plan, quality assurance/quality control methodologies, and data compilation and interpretation approaches were evaluated and endorsed by the US Environmental Protection Agency's Emission Measurement Center (EMC) and Method 9 experts from EPA Region VI (Dallas, Texas) and EPA Region VIII (Denver, Colorado) prior to collection of any field data. In addition, the State of Alaska Division of Air Quality, Anchorage, Alaska; State of Texas Air Quality Division, Austin, Texas; and the State of Utah Division of Air Quality, Salt Lake City, Utah provided regulatory oversight for the DOCS field demonstrations as well as valuable insight into the current performance limitations associated with of the application of EPA Reference Method 9.

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APPENDIX A: Analytical Methods Supporting the Experimental Design

The present field demonstration study is focused on the use of the Digital Opacity Compliance System or DOCS. The DOCS, which is an innovative technology that employs digital imaging technology for quantifying visible opacity, has been developed and field tested as a technically defensible and economically competitive alternative to Method 9. The DOCS uses a commercial-off-the-shelf (COTS) digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using statistical computer software. Therefore, there are no unique analytical methods for the technology user beyond taking the digital photographs.

In the field application of the DOCS technology, digital photographs of visible emissions were taken from valid positions according to codified Method 9 specifications. Once downloaded to a laptop or desktop computer on which the DOCS computer software had been installed, the digital images were evaluated for visible opacity. The initial steps in analyzing the digital image for opacity include 1) activating the DOCS opacity computer program, 2) retrieving those digital photographs that are to be evaluated for visible opacity and 3) using the computer program to draw an analysis box (or grid) around that portion of the visible emissions that will be analyzed (Figure A-1).

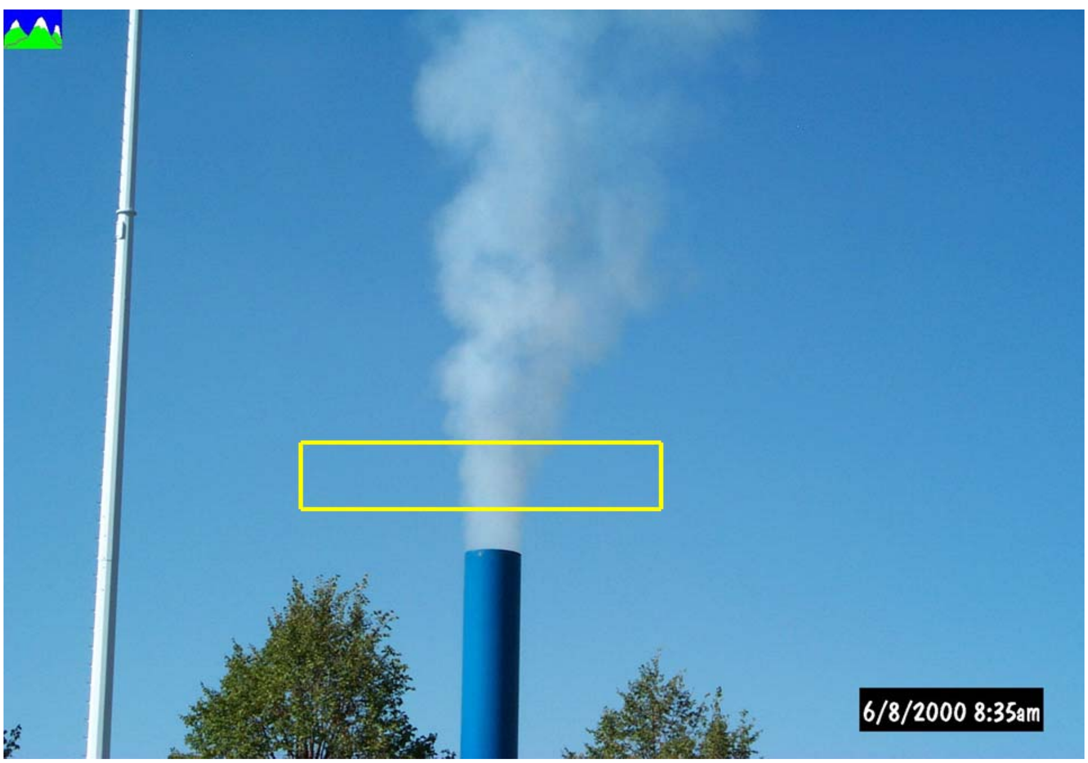

Figure A-1 Application of the DOCS Software

After the computer software selects the purity of color (*i.e.*, saturation) that best corresponds to the background, the opacity of the image is calculated based on the pixels contained in the analysis box. The size and shape of the analysis box, which is controlled by the user of the software, must be chosen judiciously because the final opacity measurement will ultimately depend on what part of the image the DOCS software identifies as background.

To ensure statistical validity in the opacity estimates, an eight-member panel consisting of federal government civilian personnel, US military personnel and federal government contractors estimated the opacity of each smoke plume captured as a digital image by using the DOCS computer software. Each panel member was provided a compact disc that contained all of the digital photographs taken from the respective smoke school as well as the DOCS computer software and user guide. The panel members were required to work independently to estimate the plume opacity of each digital photograph using the furnished computer software. Once panel members had completed their analyses, the opacity results were transferred and stored electronically in a relational database for subsequent statistical evaluation. An independent quality control officer was assigned the responsibility of maintaining the integrity of all opacity data including the opacity results generated from the EPA-certified transmissometer, against which the DOCS and human observer opacity data were compared.

Beyond the opacity estimates, the weather conditions at each of the field demonstration sites were monitored. During the field demonstrations, on-site field personnel recorded the values of specific climatic parameters including 1) mean air temperature, 2) average wind speed, 3) maximum wind speed, 4) wind direction, 5) sky conditions, 6) relative humidity, 7) visibility, 8) barometric pressure, 9) precipitation, 10) horizontal sun angle and 11) vertical sun angle. Methods used to estimate the value of each climatic parameter are summarized in Table A-1.

Table A-1 Methods Used to Estimate Weather Conditions

Parameter	**Method**
Mean temperature	Standard liquid thermometer (Eastern Technical Associates, Inc.)
Average wind speed	Standard anemometer (Eastern Technical Associates, Inc.)
Maximum wind speed	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Wind direction	Standard anemometer (Eastern Technical Associates, Inc.)
Sky conditions	Visual observation
Relative Humidity	Sling Psychrometer (Eastern Technical Associates, Inc.)
Visibility	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Barometric Pressure	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Precipitation	National Weather Service (National Oceanic and Atmospheric Administration – www.nws.noaa.gov)
Horizontal Sun Angle	Magnetic compass (Eastern Technical Associates, Inc.)
Vertical Sun Angle	Abney level (Eastern Technical Associates, Inc.)

APPENDIX B: Data Quality Assurance/Quality Control Plan

1.0 INTRODUCTION

The US Environmental Protection Agency (EPA) quality assurance policy requires that all projects conducted for or on behalf of the EPA that involve the generation of environmental data be planned and documented in an Agency-approved quality assurance project plan (QAPP). The QAPP, which describes how quality assurance (QA) and quality control (QC) activities will be implemented during the life cycle of a program, project or task, must be approved by the Agency prior to the start of any data collection. In the current study, the ESTCP demonstration plan (demo plan) will serve the same function as the QAPP and the EPA EMC has approved its implementation.

To generate environmental data of the appropriate quality for decision-making, a sampling program should consist of three distinct phases including planning, implementation and assessment. The first phase of the sampling program is characterized by the development of the Data Quality Objectives (DQOs) using the DQO process or similar systematic data quality-planning tool. DQOs provide statements about the expectations and data quality requirements of the decision-maker. In the second phase of the program, the QAPP translates these expectations and data quality requirements into measurement performance specifications required to satisfy the decision-maker's needs. In the third phase, the Data Quality Assessment (DQA) process is used to evaluate the data and to draw defensible conclusions from the data set. The following sections describe the basic approach for applying the EPA DQO and DQA processes to evaluate the equivalency of the digital opacity compliance system (DOCS) to EPA Reference Method 9.

2.0 DATA QUALITY OBJECTIVES (DQO) PROCESS

The DQO process is a strategic planning approach based on the scientific method that is used to prepare for a data collection activity. It provides a systematic procedure for defining the criteria that a data collection design should satisfy including when to collect samples, where to collect samples, the tolerable level of decision errors for the study, and how many samples to collect. By using the DQO Process, the decision-maker ensures that the type, quantity and quality of environmental data used in decision-making will be appropriate.

The DQO process consists of seven steps, which are described below. The output from each step influences the choices that will be made later in the process. Even though the DQO Process is depicted as a linear sequence of steps, in practice, it is iterative, *i.e.*, the outputs from one step may lead to reconsideration of prior steps. The following sections illustrate the application of the DQO process to generate sampling performance criteria for evaluating the potential for an opacity measurement technology to be considered as a viable alternative to EPA Reference Method 9.

Step 1: State the Problem

Step 2: Identify the Decision

Step 3: Identify the Inputs to the Decision

Step 4: Define the Study Boundary

Step 5: Develop a Decision Rule

Step 6: Specify Tolerable Limits on Decision Errors

Step 7: Optimize the Sampling Design

STEP 1: STATE THE PROBLEM

The purpose of this step is to define the problem so that the focus of the study will be unambiguous.

Federal opacity standards for various industries are found in 40 CFR Part 60 (*Standards of Performance for New and Modified Stationary Sources*). These standards require the use of EPA Reference Method 9 for the determination of visible emissions by trained and certified human observers. While EPA Reference Method 9 has an extensive history of successful employment, its reliance on human observation renders it vulnerable to inaccurate and/or biased interpretation of results.

Because of concerns regarding the reliability of opacity estimates obtained by employing EPA Reference Method 9, there is a clear need for the development of well tested and objective opacity measurement alternatives. Use of a digital opacity photographic evaluation system has the potential for minimizing both the costs associated with evaluating plume opacity and the subjectivity inherent in employing human observers for opacity estimation. The scope of the present study has been formulated to statistically evaluate whether the digital optical compliance system (DOCS) is as accurate and reliable as EPA Method 9 in quantifying visible opacity.

STEP 2: IDENTIFY THE DECISION

The purpose of this step is to define the decision statement that the study will attempt to resolve.

The principal question that this study will attempt to resolve is formulated as follows: "Is the DOCS as accurate and reliable in estimating plume opacity as EPA Reference Method 9?" The alternative actions that could result from resolution of the principal study question are 1) DOCS *is* as accurate and reliable in estimating plume opacity as EPA Reference Method 9 and, therefore, is a suitable alternative for estimating visible emissions or 2) DOCS *is not* as accurate and reliable in estimating plume opacity as EPA Reference Method 9 and, therefore, is not an equivalent alternative.

STEP 3: IDENTIFY THE INPUTS TO THE DECISION

The purpose of this step is to identify the informational inputs that will be required to resolve the decision statement and determine which inputs require environmental measurements.

To determine whether DOCS is capable of estimating visible emissions as accurately and reliably as EPA Reference Method 9, DOCS will be employed to estimate the opacity of visible emissions produced from a smoke generator used during a series of EPA visible-emissions-certification programs (*i.e.*, smoke schools). The smoke generator will be equipped with an in-line transmissometer that will establish the "true" or reference baseline opacity level against which DOCS will be evaluated.

The primary sources of information to resolve the principal study question will consist of the opacity readings recorded simultaneously by the 1) smoke generator as measured by an in-line transmissometer and 2) digital opacity compliance system (DOCS). The difference in opacity measurements recorded by the in-line transmissometer positioned in the stack of the smoke generator and those opacity readings recorded by DOCS will generate the type of data required for defensible decision-making.

STEP 4: DEFINE THE STUDY BOUNDARY

The purpose of this step is to define the spatial and temporal boundaries that are covered by the decision statement.

The characteristics that define the population of interest are the opacity levels for white and black smoke as measured by the 1) in-line transmissometer and 2) digital opacity compliance system (DOCS). Spatially, the decision resulting from resolving the principal study question will apply to any and all situations in which EPA Reference Method 9 would be utilized to estimate visible emissions.

The timeframe over which opacity data will be collected during the present study will correspond to the duration of the smoke school field certification activities. Specific opacity data will be collected when the smoke school contract coordinator indicates that the plume emission is stable and that the opacity level should be estimated.

STEP 5: DEVELOP A DECISION RULE

The purpose of this step is to define the parameter of interest, specify the action level, and integrate previous DQO outputs into a single statement that describes a logical basis for choosing among alternative actions.

The parameter of interest in this study is the absolute value of the *mean difference* between the in-line transmissometer opacity readings estimated over the full range of opacity levels and the opacity readings recorded by the digital opacity compliance system (DOCS). The in-line transmissometer opacity readings will serve as a reference baseline and subtraction of those data from the opacity readings reported by the digital opacity compliance system (DOCS) will be used to estimate the *mean difference* between the two opacity measurement systems. Since EPA Reference Method 9 permits a human observer's estimate of visible opacity to deviate by as much as 7.5% (on average) from the transmissometer opacity reading and still qualify for certification, a parameter value (*mean difference*) of 7.5% will serve as the action level for the current study.

If the absolute value of the *mean difference* in plume opacity measured between the in-line transmissometer and the digital opacity compliance system (DOCS) is statistically *less than or equal* to 7.5% at the *99% confidence level*, the decision-maker will conclude that the digital opacity compliance system (DOCS) *is* equivalent to EPA Reference Method 9. On the other hand, if the absolute value of the *mean difference* in estimated plume opacity measured between the in-line transmissometer and the digital opacity compliance system (DOCS) is statistically

greater than 7.5% at the *99% confidence level*, the decision-maker will conclude that the digital opacity compliance system (DOCS) *is not* equivalent to EPA Reference Method 9.

At present, there are no known limitations or inherent biases associated with using the digital opacity compliance system (DOCS) to estimate visible opacity. Moreover, the current sampling design, which specifies the use of randomly chosen opacity levels as well as the use of multiple cameras and certified smoke readers positioned at various locations surrounding the stack, should significantly reduce the impact of any inherent bias of DOCS on conclusions drawn from the final test results. However, to fully characterize the limitations of DOCS, the degree of bias (or systematic error) associated with DOCS will be evaluated as a function of the visible opacity level as well as camera position relative to the sun and stack. By estimating the difference between the average DOCS opacity readings and the true opacity (as measured by an EPA certified transmissometer) at each increment of opacity (from 0 to 100% opacity for both black and white smoke) and for each camera position, the identification of any biases associated with the application of DOCS will be quantified. If the level of bias is found to be significant, it will be fully characterized and identified as an inherent limitation of the system.

The precision of DOCS will be reflected in the variance and standard deviation estimated from sampling data (*i.e.*, differences in paired opacity readings). By collecting hundreds of randomly selected paired opacity measurements for each site location, it is anticipated that the effect of random errors will be minimized and, therefore, site-specific data will be characterized by relatively high precision. However, in developing the Phase I experimental design, it was recognized that the DOCS performance could vary significantly depending on climatic conditions. In other words, temperature, humidity and/or other environmental factors could potentially change the response and accuracy of DOCS in measuring visible opacity. In the present study, the overall accuracy and reproducibility of DOCS will be determined by comparing the precision of the system (as reflected by the variance and standard deviation of paired opacity readings) at each of the physical locations. Significant variation in the level of DOCS precision as a function of location will not only highlight the importance of climatic/environmental conditions on system usability but would also suggest another potential limitation of the technology.

Finally, in comparing the ability of DOCS to accurately measure visible opacity relative to EPA Method-9-certified smoke readers, no DOCS data will be excluded from the overall analysis. In other words, all DOCS data will be included in the statistical comparison with EPA Method-9-certified smoke readers (*i.e.*, those human observers whose overall opacity recordings during certification testing were within $\pm$ 7.5 % of the true opacity level and had no single opacity reading greater than
$\pm$ 15% of the true opacity level). The concept of outliers has no particular relevance in evaluating the DOCS technology since the recorded visible opacity from this system is a function of both the DOCS software *and* how effectively the operator interprets and captures the plume (*i.e.*, how the control volume is drawn) within the digital photograph. Of greater significance, however, is the need to establish the inherent variability associated with an operator's use of DOCS to estimate visible opacity. By employing multiple individuals to interpret the identical digital photographs with the DOCS software, it is anticipated that one of the most valuable results from the current study will be a reliable estimate of the inherent variability of DOCS.

STEP 6: SPECIFY LIMITS ON DECISION ERRORS

The purpose of this step is to specify the decision-maker's tolerable limits on decision errors, which are used to establish performance goals for the data collection design.

There are two types of decision errors that can occur based on the decision-maker's interpretation of sampling data: false positive and false negative decision errors. In the comparison of paired opacity measurements, a false positive decision error will be defined to occur when the decision-maker concludes (based on field measurements) that the absolute value of the *mean difference* in visible opacity between measurements is *equal to or less than* 7.5% when, in fact, it is *greater*. Conversely, a false negative decision error would occur when the decision-maker concludes (based on field measurements) that the absolute value of the *mean difference* in visible opacity between measurements is *equal to or less than* 7.5% when, in fact, it is *greater.*
An action level is defined as the value of the parameter of interest (*i.e.*, *mean difference*) that would cause the decision-maker to choose between alternative actions. For the current study, the action level (AL) will be established as 7.5%. In other words, if the absolute value of the *mean difference* in visible opacity between measurements is statistically greater than 7.5%, the decision-maker would be led to conclude that the digital opacity compliance system (DOCS) *is not* equivalent to EPA Method 9. Alternatively, if the absolute value of the *mean difference* in visible opacity between measurements is statistically equal to or less than 7.5%, the decision-maker would conclude that the digital opacity compliance system (DOCS) *is* equivalent to EPA Reference Method 9.

Statistically, a false positive decision error is referred to as a Type I error and its occurrence rate (or probability) is normally represented by the letter "α." For example, if the decision-maker desired to limit the risk of committing a false positive decision error to one (1) percent, "α" would be assigned a value of 0.01. Similarly, a false negative decision error is referred to as a Type II error and is typically represented by the letter "β." The tolerable risk (or probability) of committing a Type II error is also established by the decision-maker (*e.g.*, assigning β equal to 0.01 is equivalent to establishing a false negative error rate of 1%).

In the current study, the decision of whether the digital opacity compliance system (DOCS) is equivalent to EPA Method 9 depends on whether the absolute value of the *mean difference* between opacity readings between an in-line transmissometer and DOCS can be shown to be equal to or less than 7.5%. Since the direction of the *mean difference* (*i.e.*, positive or negative) is not relevant in making a decision, the tolerable false positive and false negative decision error rates (α and β) should be identical. In the present study, the false positive and false negative decision error rates both will be assigned a value of 0.01.

In addition to specifying the false positive and false negative decision error rates, the decision-maker is required to specify a range of possible parameter values near the action level where the consequences of committing false negative decision errors are relatively minor (in the DQO process this is called the gray region). In statistics, the width of this interval is called the minimum detectable difference and is expressed as the Greek letter delta (Δ). Since the EPA Reference Method 9 protocol requires visible emission observers to record plume opacities in 5% intervals, for the present study, Δ will be arbitrarily set to half of this value, *i.e.*, 2.5%.

STEP 7: OPTIMIZE THE SAMPLING DESIGN

The purpose of this step is to identify a resource-effective data collection design for generating data that are expected to satisfy the DQOs.

The minimum number of samples (*n*) necessary to satisfy the established decision error rates (α, β) can be estimated by using Equation 1.0.

$$n = \frac{\sigma^2 \bullet \left(Z_{1\text{-}\beta} + Z_{1\text{-}\alpha}\right)^2}{\Delta^2} + (0.5) \bullet Z_{1\text{-}\alpha}^2 \qquad (1.0)$$

where

n = minimum number of samples required to meet rates of decision errors

σ = estimated standard deviation (from preliminary studies)

σ^2 = estimated variance (from pilot study)

$Z_{1\text{-}\beta}$ = the (1-β) percentile of the standard normal distribution (from standard statistical tables)

$Z_{1\text{-}\alpha}$ = the (1-α) percentile of the standard normal distribution (from standard statistical tables)

Δ = minimum detectable difference

Short-term visible opacity studies conducted at Hill AFB using the digital opacity compliance system (DOCS) indicated that, at the 30% opacity level, this measurement system has an apparent standard deviation of 3.44% (σ). Substituting a standard deviation (σ) of 3.44%, a minimum detectable difference (Δ) of 2.5%, and tolerable false positive (α) and false negative (β) decision error rates of 0.01 into Equation 1.0, generates forty-three (43) as the *minimum* number of samples required to satisfy the quantitative DQOs (note that from standard statistical tables, the values of $Z_{1\text{-}\alpha}$ and $Z_{1\text{-}\beta}$ are equal to 2.3). In actuality, since the digital opacity compliance system (DOCS) will be evaluated against EPA Method 9 using both white *and* black smoke, the *minimum* number of samples required to satisfy the DQOs should be twice the estimated amount or eighty-six (86) samples (43 samples of both black and white smoke). In practice, the minimum number of samples estimated using Equation 1.0 identifies only a lower bound for the required number of samples. To ensure that the data set will be of a sufficient size to draw defensible conclusions (*i.e.*, decisions supported by a relatively high level of confidence), the decision-maker should evaluate the cost of obtaining substantially more samples than the minimum number estimated from using Equation 1.0. Once the data have been collected, the data quality assessment (DQA) process should be applied so that defensible conclusions may be drawn from the data set.

3.0 DATA QUALITY ASSESSMENT (DQA) PROCESS

Data quality assessment (DQA) is the scientific and statistical evaluation of data to determine if the data obtained are of the right type, quality and quantity to support their intended use. The

five steps of the USEPA data quality assessment (DQA) process include 1) review the data quality objectives and sampling design, 2) conduct a preliminary data review, 3) select the statistical test, 4) verify the assumptions of the statistical test and 5) draw conclusions from the data.

The first step in the DQA process will involve a review of the DQO outputs and sampling design to ensure consistency. Typical activities that characterize this step include the review of study objectives and assigning the tolerable probability limits on decision errors. During the second step of the DQA process, quality assurance information is reviewed to ensure that the data quality conforms to the decision-makers requirements and to identify any particular patterns or relationships.

Following the completion of the preliminary data review, the appropriate statistical procedure for analyzing the experimental data is selected during the third step of the DQA process. For example, in the present study, since the measurement of visible opacity recorded by the in-stack transmissometer will be compared with a simultaneous visibility opacity measurement recorded by the DOCS, evaluation of the absolute value mean of the paired differences will be employed as a measure of method equivalency. Specifically, a paired *t*-test will be used to assess whether the absolute value of the true mean of the paired differences (δ) is statistically equal to or less than 7.5%.

In the fourth step of the DQA process, the underlying assumptions of the statistical test are examined to determine if corrective action, which may include the possibility of collecting additional data, is necessary. Interpretation of the experimental data results and the drawing of defensible study conclusions characterize the fifth step of the DQA process. The following section provides a brief discussion of how the paired data set may be used to estimate the absolute value of the mean difference in opacity readings between the in-line stack transmissometer and DOCS data. An example of the data analysis approach is provided to illustrate how defensible conclusions may be drawn from the data set.

4.0 STATISTICAL PROCEDURES FOR EVALUATING EQUIVALENCY OF ALTERNATIVES TO EPA REFERENCE METHOD 9

A standard statistical procedure for comparing the equivalency of two measurement methods is to employ significance testing. In significance testing, a null hypothesis (H_o) is developed that will be assumed to be true in the absence of strong quantitative evidence to the contrary. The strength of the data may be evaluated statistically using a paired sample *t*-test. The results of the paired sample *t*-test will provide the basis for either rejecting or not rejecting the null hypothesis, H_o.

The null hypothesis (H_o) for the present study may be stated as follows: "*the absolute value of the true mean difference between the transmissometer and the DOCS opacity measurement methods is greater than 7.5%.*" This statement reflects the decision-maker's initial assumption that the two opacity measurement methods are not equivalent. To reach a determination that the DOCS is equivalent to EPA Method 9, the strength of the data must be sufficient to reject the null hypothesis. Similarly, the alternative hypothesis (H_a) may be constructed as follows: "*the absolute value of the true mean difference between the transmissometer and the DOCS opacity measurement method is equal to or less than 7.5%.*" If the strength of the data is sufficient to

reject the null hypothesis, the decision-maker will conclude that the alternative hypothesis (H_a) is true (*i.e.*, DOCS is equivalent to EPA Method 9).

In statistical terms, these hypotheses can be presented as follows:

Null Hypothesis (H_0): $\delta_0 > 7.5\%$

Alternative Hypothesis (Ha): $\delta_0 \leq 7.5\%$

Where

δ_0 = true mean difference (opacity measured using DOCS – opacity measured using transmissometer)

Since the *true mean difference* between the two visible opacity measurement methods (δ_o) can never be known exactly, it must be estimated by calculating the average of the differences. Equation 1.1 may be used to calculate the average of the paired opacity differences from the sampling data.

$$\bar{d} = \frac{\sum_{i=1}^{i=n} d_i}{n} = \frac{1}{n} \bullet \sum_{i=1}^{i=n} \left(\left| y_{1i} - y_{2i} \right| \right) \tag{1.1}$$

Where

$\bar{d}$ = average absolute difference between paired opacity measurements

$y_{1,i}$, $y_{2,i}$ = opacity measurements i recorded by the transmissometer and DOCS, respectively

n = number of paired measurements

Equations 1.2 and 1.3 may be used to estimate the sample variance and standard error of the average differences between opacity readings, respectively.

$$s_d^{\ 2} = \frac{\sum_{i=1}^{i=n} \left(\left| d_i \right| - \bar{d} \right)^2}{n-1} \tag{1.2}$$

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}} \tag{1.3}$$

Where

d_i = difference between paired opacity measurements

s_d^2 = sample variance

s_d = standard error

To employ the *paired* t-*test* to draw defensible conclusions from the data set requires that the decision-maker select a level of significance (α) from which a critical *t*-value may be estimated. The critical *t*-value is compared to the test statistic to determine if the strength of the data is sufficient to reject the null hypothesis, H_o. Given an assigned level of significance, α, and degrees of freedom (n-1), the following expressions define the critical *t*-values and test-statistic (t_{test}) that are used to evaluate whether the strength of the data is sufficient to reject the null hypothesis.

$$\text{Critical } t\text{-value: } t_{\frac{\alpha}{2}, n-1}$$

$$\text{Test statistic}: t_{\text{test}} = \frac{\bar{d} - \delta_o}{\frac{s_d}{\sqrt{n}}}$$

Where

δ_0 = absolute value of mean difference (action level – assumed equal to 7.5%)

Once the critical *t*-value and test statistic (t_{test}) have been estimated, the following test conditions are employed to determine the strength of the field data:

Test Condition: If $t_{\text{test}} < t_{\frac{\alpha}{2}, n-1}$, then the null hypothesis, H_0, is rejected.

Test Condition: If $t_{\text{test}} > t_{\frac{\alpha}{2}, n-1}$, the data do not support rejection of the null hypothesis, H_0.

The following example illustrates the use of these statistical principles to evaluate the ability of DOCS to measure plume opacity as accurately as EPA Method 9.

EXAMPLE

In the present example, it is assumed that the decision-maker has applied the DQO process and has determined that to limit the false positive and negative decision error rates to 5%, a minimum of thirteen (13) samples should be taken. The following table provides a summary of the data from the 13 paired opacity measurements recorded by an EPA Method 9 in-stack transmissometer and DOCS. Given the results of the field measurements, the decision-maker desires to know whether DOCS is capable of measuring plume opacity as accurately as EPA Method 9 at the 5% significance level (α is 0.05). In other words, do the data support a decision with 95% confidence?

Measurement Number	Transmissometer Opacity Measurement (*T*)	DOCS Opacity Measurement (*D*)	Absolute Value of the Paired Differences: *T* – *D*
1	15	12.3	2.7
2	50	63.8	13.8
3	30	45.1	15.1
4	45	54.4	9.4
5	65	79.3	14.3
6	90	88.2	1.8
7	5	9.1	4.1
8	25	36.2	11.2
9	20	14.2	5.8
10	40	52.9	12.9
11	55	69.9	14.9
12	95	85.7	9.3
13	35	42.6	7.6

Statistical Evaluation Process - (*Paired* t-*test*)

Step 1. Estimate the critical *t*-value from standard statistical tables using a 0.05 level of significance and 12 (*i.e.*, 13 – 1) degrees of freedom. From standard tables, the following critical *t*-value was found:

$$t_{\frac{\alpha}{2},\, n-1} = t_{0.025,12} = 2.179$$

Step 2. Estimate the mean of the *absolute value* of the paired differences.

$$\bar{d} = [(2.7) + (13.8) + (15.1) + \ldots + (7.6)]/13 = 9.45$$

Step 3. Estimate the variance (s_d^2) and standard deviation (s_d) of the paired differences using Equation 1.2.

$$s_d^2 = \frac{\sum_{i=1}^{i=n}\left(\left|d_i\right| - \bar{d}\right)^2}{n-1} = [(2.7\text{-}9.45)^2 + (13.8\text{-}9.45)^2 + (15.1\text{-}9.45)^2 + \ldots + (7.6\text{-}9.45)^2]/12$$

$$= 22.38$$

$$s_d = \sqrt{22.38} = 4.73$$

Step 4. Estimate the standard error of the paired differences using Equation 1.3.

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}} = \frac{4.73}{\sqrt{13}} = 1.31$$

Step 5. Calculate the test statistic (t_{test}) and compare it to the critical t-value to determine if the null hypothesis can be rejected at the 5% significance level.

$$\text{Test statistic}: t_{\text{test}} = \frac{\bar{d} - \delta_o}{\frac{s_d}{\sqrt{n}}} = \frac{9.45 - 7.5}{1.31} = 1.49$$

Since $t_{\text{test}} < t_{\frac{\alpha}{2}, n\text{-}1}$ (*i.e.*, 1.49 < 2.179), there is insufficient evidence to **reject** the null hypothesis, H_0.

By *not* rejecting the null hypothesis, H_o, the decision-maker would conclude that the *absolute difference* between values measured by the digital opacity compliance system (DOCS) and the transmissometer opacity measurement system is *greater* than 7.5%. In other words, the decision would be that DOCS does *not* measure plume opacity as accurately as EPA Reference Method 9 and therefore, the two measurement systems *are not* equivalent. It is important to recognize that whenever the null hypothesis, H_o, *is not* rejected, the *power* of the significance test should be evaluated to ensure that the test has adequate sensitivity to allow the decision-maker to reach a defensible conclusion. An equivalent alternative to evaluating the power of the significance test is to calculate the required sample size (m) necessary to achieve the false positive and negative decision error rates and compare it to the actual number of samples taken (n). The required sample size (m) necessary to satisfy the established decision error rates (α, β) may be estimated using Equation 1.4.

$$m = \frac{s_d^{\,2} \bullet \left(Z_{1\text{-}\alpha} + Z_{1\text{-}\beta}\right)^2}{\left(\bar{d} - \delta_o\right)^2} + 0.5\left(Z_{1\text{-}\alpha}\right)^2 \qquad (1.4)$$

Test Condition:

If $m < n$ The decision-maker would conclude that a sufficient number of samples have been taken to determine (with 95% confidence) that the *true mean difference* is above 7.5% and therefore DOCS is not equivalent to EPA Method 9 (acceptance of the null hypothesis).

If $m > n$ The decision-maker would conclude that an insufficient number of samples have been taken to support a decision at the desired level of confidence. The decision-maker would determine that the data *suggest* that the *true mean difference* is above 7.5% and that DOCS is not equivalent to EPA Method 9. However, that decision *cannot* be supported at the 95% confidence level.

Step 6. Calculate the required sample size (m) necessary to satisfy the established decision error rates (α, β) can be estimated by using Equation 1.4. Note that $Z_{1-\alpha}$ = $Z_{1-\beta}$ = 1.65 when
$\alpha = \beta = 0.05$.

$$m = \frac{22.38 \bullet (1.65 + 1.65)^2}{(9.45 - 7.5)^2} + 0.5 \bullet (1.65)^2 = 32.6\,(33\,\text{samples})$$

Since $m>n$, the decision maker would conclude that DOCS is not statistically equivalent to EPA Method 9 (*i.e.*, acceptance of the null hypothesis) but that an insufficient amount of data was collected to support that decision at the 95% confidence level. Alternatively, the decision-maker could collect additional data to increase the level of confidence in the decision.

APPENDIX C EPA Reference Method 9

EMISSION MEASUREMENT TECHNICAL INFORMATION CENTER
NSPS TEST METHOD

Prepared by **Emission Measurement Branch** **EMTIC TM-009**
Technical Support Division, OAQPS, EPA October 25, 1990

Method 9 - Visual Determination of the Opacity of Emissions from Stationary Sources

INTRODUCTION

(a) Many stationary sources discharge visible emissions into the atmosphere; these emissions are usually in the shape of a plume. This method involves the determination of plume opacity by qualified observers. The method includes procedures for the training and certification of observers and procedures to be used in the field for determination of plume opacity.

(b) The appearance of a plume as viewed by an observer depends upon a number of variables, some of which may be controllable in the field. Variables which can be controlled to an extent to which they no longer exert a significant influence upon plume appearance include: angle of the observer with respect to the plume; angle of the observer with respect to the sun; point of observation of attached and detached steam plume; and angle of the observer with respect to a plume emitted from a rectangular stack with a large length to width ratio. The method includes specific criteria applicable to these variables.

(c) Other variables which may not be controllable in the field are luminescence and color contrast between the plume and the background against which the plume is viewed. These variables exert an influence upon the appearance of a plume as viewed by an observer and can affect the ability of the observer to assign accurately opacity values to the observed plume. Studies of the theory of plume opacity and field studies have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background. Accordingly, the opacity of a plume viewed under conditions where a contrasting background is present can be assigned with the greatest degree of accuracy. However, the potential for a positive error is also the greatest when a plume is viewed under such contrasting conditions. Under conditions presenting a less contrasting background, the apparent opacity of a plume is less and approaches zero as the color and luminescence contrast decrease toward zero. As a result, significant negative bias and negative errors can be made when a plume is viewed under less contrasting conditions. A negative bias decreases rather than increases the possibility that a plant operator will be incorrectly cited for a violation of opacity standards as a result of observer error.

(d) Studies have been undertaken to determine the magnitude of positive errors made by qualified observers while reading plumes under contrasting conditions and using the procedures set forth in this method. The results of these studies (field trials) which involve a total of 769 sets of 25 readings each are as follows:

(1) For black plumes (133 sets at a smoke generator), 100 percent of the sets were read with a positive error of less than 7.5 percent opacity; 99

percent were read with a positive error of less than 5 percent opacity. (Note: For a set, positive error = average opacity determined by observers' 25 observations -average opacity determined from transmissometer's 25 recordings.)

(2) For white plumes (170 sets at a smoke generator, 168 sets at a coal-fired power plant, 298 sets at a sulfuric acid plant), 99 percent of the sets were read with a positive error of less than 7.5 percent opacity; 95 percent were read with a positive error of less than 5 percent opacity.

(e) The positive observational error associated with an average of twenty-five readings is therefore established. The accuracy of the method must be taken into account when determining possible violations of applicable opacity standards.

1. PRINCIPLE AND APPLICABILITY

1.1 Principle. The opacity of emissions from stationary sources is determined visually by a qualified observer.

1.2 Applicability. This method is applicable for the determination of the opacity of emissions from stationary sources pursuant to § 60.11(b) and for visually determining opacity of emissions.

2. PROCEDURES

The observer qualified in accordance with Section 3 of this method shall use the following procedures for visually determining the opacity of emissions.

2.1 Position. The qualified observer shall stand at a distance sufficient to provide a clear view of the emissions with the sun oriented in the 140° sector to his back. Consistent with maintaining the above requirement, the observer shall, as much as possible, make his observations from a position such that his line of vision is approximately perpendicular to the plume direction and, when observing opacity of emissions from rectangular outlets (*e.g.*, roof monitors, open baghouses, noncircular stacks), approximately perpendicular to the longer axis of the outlet. The observer's line of sight should not include more than one plume at a time when multiple stacks are involved, and in any case the observer should make his observations with his line of sight perpendicular to the longer axis of such a set of multiple stacks (*e.g.*, stub stacks on baghouses).

2.2 Field Records. The observer shall record the name of the plant, emission location, facility type, observer's name and affiliation, and the date on a field data sheet (Figure 9-1). The time, estimated distance to the emission location, approximate wind direction, estimated wind speed, description of the sky condition (presence and color of clouds), and plume background are recorded on a field data sheet at the time opacity readings are initiated and completed.

Figure 9-1. Record of visual determination of opacity.

Company

Location

Test No.

Date

Type Facility

Control Device

Hours of Observation

Observer

Observer Certification Date | Observer Affiliation

Point of Emissions | Height of Discharge Point

CLOCK TIME	Initial			Final
OBSERVER LOCATION				
Distance to discharge				
Direction from discharge				
Height of observation point				
BACKGROUND DESCRIPTION				
WEATHER CONDITIONS				
Wind Direction				
Wind Speed				
Ambient Temperature				
SKY CONDITIONS (clear, overcast, % clouds, etc.)				
PLUME DESCRIPTION				
Color				
Distance Visible				
OTHER INFORMATION				

SUMMARY OF AVERAGE OPACITY

Set Number	Time	Opacity	
	Start - End	Sum	Average

Readings ranged from ___ to ___ % opacity.

The source was/was not in compliance with ___ at the time evaluation was made.

2.3 Observations. Opacity observations shall be made at the point of greatest opacity in that portion of the plume where condensed water vapor is not present. The observer shall not look continuously at the plume but instead shall observe the plume momentarily at 15-second intervals.

2.3.1 Attached Steam Plumes. When condensed water vapor is present within the plume as it emerges from the emission outlet, opacity observations shall be made beyond the point in the plume at which condensed water vapor is no longer visible. The observer shall record the approximate distance from the emission outlet to the point in the plume at which the observations are made.

2.3.2 Detached Steam Plume. When water vapor in the plume condenses and becomes visible at a distinct distance from the emission outlet, the opacity of emissions should be evaluated at the emission outlet prior to the condensation of water vapor and the formation of the steam plume.

2.4 Recording Observations. Opacity observations shall be recorded to the nearest 5 percent at 15-second intervals on an observational record sheet. (See Figure 9-2 for an example.) A minimum of 24 observations shall be recorded. Each momentary observation recorded shall be deemed to represent the average opacity of emissions for a 15-second period.

2.5 Data Reduction. Opacity shall be determined as an average of 24 consecutive observations recorded at 15-second intervals. Divide the observations recorded on the record sheet into sets of 24 consecutive observations. A set is composed of any 24 consecutive observations. Sets need not be consecutive in time and in no case shall two sets overlap. For each set of 24 observations, calculate the average by summing the opacity of the 24 observations and dividing this sum by 24. If an applicable standard specifies an averaging time requiring more than 24 observations, calculate the average for all observations made during the specified time period. Record the average opacity on a record sheet. (See Figure 9-1 for an example.)

3. QUALIFICATION AND TESTING

3.1 Certification Requirements. To receive certification as a qualified observer, a candidate must be tested and demonstrate the ability to assign opacity readings in 5 percent increments to 25 different black plumes and 25 different white plumes, with an error not to exceed 15 percent opacity on any one reading and average error not to exceed 7.5 percent opacity in each category. Candidates shall be tested according to the procedures described in Section 3.2. Smoke generators used pursuant to Section 3.2 shall be equipped with a smoke meter which meets the requirements of Section 3.3. The certification shall be valid for a period of 6 months, at which time the qualification procedure must be repeated by any observer in order to retain certification.

3.2 Certification Procedure. The certification test consists of showing the candidate a complete run of 50 plumes--25 black plumes and 25 white plumes--generated by a smoke generator. Plumes within each set of 25 black and 25 white runs shall be presented in random order. The candidate assigns an opacity value to each plume and records his observation on a suitable form. At the completion of each run of 50 readings, the score of the candidate is

determined. If a candidate fails to qualify, the complete run of 50 readings must be repeated in any retest. The smoke test may be administered as part of a smoke school or training program and may be preceded by training or familiarization runs of the smoke generator during which candidates are shown black and white plumes of known opacity.

3.3 Smoke Generator Specifications. Any smoke generator used for the purposes of Section 3.2 shall be equipped with a smoke meter installed to measure opacity across the diameter of the smoke generator stack. The smoke meter output shall display in-stack opacity based upon a pathlength equal to the stack exit diameter, on a full 0 to 100 percent chart recorder scale. The smoke meter optical design and performance shall meet the specifications shown in Table 91. The smoke meter shall be calibrated as prescribed in Section 3.3.1 prior to the conduct of each smoke reading test. At the completion of each test, the zero and span drift shall be checked and if the drift exceeds ±l percent opacity, the condition shall be corrected prior to conducting any subsequent test runs. The smoke meter shall be demonstrated, at the time of installation, to meet the specifications listed in Table 9-1. This demonstration shall be repeated following any subsequent repair or replacement of the photocell or associated electronic circuitry including the chart recorder or output meter, or every 6 months, whichever occurs first.

TABLE 9-1 - SMOKE METER DESIGN AND PERFORMANCE SPECIFICATIONS

Parameter	Specification
a. Light Source	Incandescent lamp operated at nominal rated voltage
b. Spectral response of photocell	Photopic (daylight spectral response of the human eye - Citation 3)
c. Angle of view	15B maximum total angle
d. Angle of projection	15B maximum total angle
e. Calibration error	±3% opacity, maximum
f. Zero and span drift	±1% opacity, 30 minutes
g. Response time	5 seconds

3.3.1 Calibration. The smoke meter is calibrated after allowing a minimum of 30 minutes warm-up by alternately producing simulated opacity of 0 percent and 100 percent. When stable response at 0 percent or 100 percent is noted, the smoke meter is adjusted to produce an output of 0 percent or 100 percent, as appropriate. This calibration shall be repeated until stable 0 percent and 100 percent opacity values may be produced by alternately switching the power to the light source on and off while the smoke generator is not producing smoke.

3.3.2 Smoke Meter Evaluation. The smoke meter design and performance are to be evaluated as follows:

3.3.2.1 Light Source. Verify from manufacturer's data and from voltage measurements made at the lamp, as installed, that the lamp is operated within ±5 percent of the nominal rated voltage.

3.3.2.2 Spectral Response of Photocell. Verify from manufacturer's data that the photocell has a photopic response; *i.e.*, the spectral sensitivity of the cell shall closely approximate the standard spectral-luminosity in (b) of Table 91.

3.3.2.3 Angle of View. Check construction geometry to ensure that the total angle of view of the smoke plume, as seen by the photocell, does not exceed 15°. The total angle of view may be calculated from: $I = 2 \tan^{-1} (d/2L)$, where I = total angle of view; d = the sum of the photocell diameter + the diameter of the limiting aperture; and L = the distance from the photocell to the limiting aperture. The limiting aperture is the point in the path between the photocell and the smoke plume where the angle of view is most restricted. In smoke generator smoke meters this is normally an orifice plate.

3.3.2.4 Angle of Projection. Check construction geometry to ensure that the total angle of projection of the lamp on the smoke plume does not exceed 15°. The total angle of projection may be calculated from: $I = 2 \tan^{-1} (d/2L)$, where I = total angle of projection; d = the sum of the length of the lamp filament + the diameter of the limiting aperture; and L = the distance from the lamp to the limiting aperture.

3.3.2.5 Calibration Error. Using neutral-density filters of known opacity, check the error between the actual response and the theoretical linear response of the smoke meter. This check is accomplished by first calibrating the smoke meter according to Section 3.3.1 and then inserting a series of three neutral-density filters of nominal opacity of 20, 50, and 75 percent in the smoke meter pathlength. Filters calibrated within 2 percent shall be used. Care should be taken when inserting the filters to prevent stray light from affecting the meter. Make a total of five nonconsecutive readings for each filter. The maximum error on any one reading shall be 3 percent opacity.

3.3.2.6 Zero and Span Drift. Determine the zero and span drift by calibrating and operating the smoke generator in a normal manner over a 1-hour period. The drift is measured by checking the zero and span at the end of this period.

3.3.2.7 Response Time. Determine the response time by producing the series of five simulated 0 percent and 100 percent opacity values and observing the time required to reach stable response. Opacity values of 0 percent and 100 percent may be simulated by alternately switching the power to the light source off and on while the smoke generator is not operating.

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